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PRACTICAL APPLICATIONS OF THE EARTH-CURRENT METER

By Burton McCollum and K. H. Logan

TECHNOLOGIC PAPERS OF THE BUREAU OF STANDARDS, No. 351

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PRACTICAL APPLICATIONS OF THE EARTH-CURRENT METER

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ABSTRACT

Because electrolytic corrosion of underground structures is roughly proportional to the leakage current which leaves these structures for the earth, an instrument for measuring this current is needed by engineers engaged in electrolysis testing and research. After several years of experimentation the Bureau of Standards has succeeded in developing an instrument for this purpose, and the results of its use in the field indicate that it is very satisfactory and of great practical value.

The instrument and accessories permit the determination of the resistivity and potential gradient of the soil adjacent to a pipe. A formula is developed for determining the rate of discharge of current by the pipe from these data. The formula involves a constant determined experimentally, and the method of determination of this constant is described.

Instructions are given for the several uses of the apparatus. The care of the instrument and the precautions necessary for obtaining reliable data are discussed.

In the last part of the paper the interpretation of data is considered and the results of field work are quoted to show that the earth-current meter gives more reliable information regarding electrolysis conditions than can be obtained otherwise.

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I. THE EARTH-CURRENT METER

1. ORIGIN AND PURPOSE OF THE EARTH-CURRENT METER

Engineers engaged in electrolysis research work have long felt the need of a definite and accurate means of determining both the polarity of pipes with respect to earth and the current density in the earth at any point, especially in the immediate vicinity of pipes under investigation. Realizing the vital importance of meeting this need, the Bureau of Standards has conducted an extensive research on the measurement of intensity of current discharge from pipes to earth. This research has resulted in the development of an instrument known as the earth-current meter, which meets in a satisfactory degree the requirements of a practical instrument. The instrument has now been in use for several years by a number of consulting and utility engineers, and its reliability and usefulness have been demonstrated under a variety of field conditions.

The earth-current meter is designed for the measurement of soil resistivity and of current density in the earth. These measurements permit the calculation of the density of the current discharge from structures buried in direct contact with the earth. The discharge at the surface of cable sheaths in ducts can not be determined on account of the effects of the ducts. For determining whether the rate of discharge of current from a point where a pipe failure has occurred is sufficient to account for rapid corrosion, the instrument has proven particularly valuable, and this use of the instrument is so simple that anyone familiar with electrical instruments can secure the desired data.

A broader application of the earth-current meter is the determination of the adequacy of or the need for electrolysis mitigation. In such cases the instrument is used to determine the rate of discharge of current and hence the rate of electrolytic corrosion at such points as other methods of testing and the relations of the underground structures indicate to be the points of greatest hazard.

In such cases the earth-current meter is not intended to supplant the older methods of testing, but to furnish more specific and reliable data at critical points, the importance of which justifies the additional labor and expense which its use involves.

It will be shown in the course of this paper that in many locations the electrical relations between the underground structures are very complicated, and that in the use of the older methods of testing a number of errors are involved which under some conditions make the significance of observations doubtful. The earth-current meter has been designed to avoid the sources of error in the older methods, and because of the way in which it is used much more exact and detailed information is obtained than can be secured otherwise.

It is to be expected that the collecting of detailed information will require more time and effort than the gathering of general information, and usually it is not worth while to secure this detailed data except at important points. The determination of the locations which may yield the most valuable data requires the exercise of judgment based largely on experience. It is for this reason rather than because of any complication or delicacy of the instrument that it is recommended that the determination of electrolysis conditions be assigned to some one of considerable practical experience in electrolysis testing and in the interpretation of the data so obtained.

2. THEORY OF THE INSTRUMENT

The density of current flowing between two points in a homogeneous soil can be calculated from the earth resistivity and the voltage gradient between the points. The earth-current meter is based upon this principle, although in its operation neither the resistivity nor the true potential drop need be determined.

The principle of the new method can best be understood by reference to Figure 1, which is a diagrammatic representation of the apparatus. An excavation is here assumed to simplify the explanation of the principle of the method. It will be shown later how the method can be applied in many cases with very little or no excavation.

Let us assume that the pipe, *1*, of Figure 1 is discharging current in all directions as indicated by the arrows, *2*. Four electrodes, P_1, C_1, C_2, and P_2, may be pressed against the wall of a trench immediately adjoining the pipe on whatever side the current density is to be measured. For convenience, these several electrodes may be mounted on a single insulating frame, *3*. This assembly of the four electrodes in a fixed relation to each other will hereafter be referred to as the "contactor." Two of the electrodes, P_1 and P_2, are connected to a suitable voltage indicator, *6*, which need not read in any particular unit.

Suppose now a current I_c be caused to flow between the electrodes C_1 and C_2 through the earth from the battery, *4*, and be measured by an ammeter, *5*. It will be evident that this current distributes itself in all directions through the earth and produces a certain voltage drop between the electrodes P_1 and P_2 due to the resistance in the earth immediately surrounding the group of electrodes. This voltage drop between the electrodes P_1 and P_2 will be indicated by the voltmeter, *6*, and will be proportional to the current flowing between the electrodes C_1 and C_2, to the resistivity of the surrounding earth, and to a constant depending on the size and arrangement of electrodes. If E_c is the voltage between the electrodes P_1 and P_2, and if θ_c is the corresponding deflection of the voltage indicator, *6*, we have

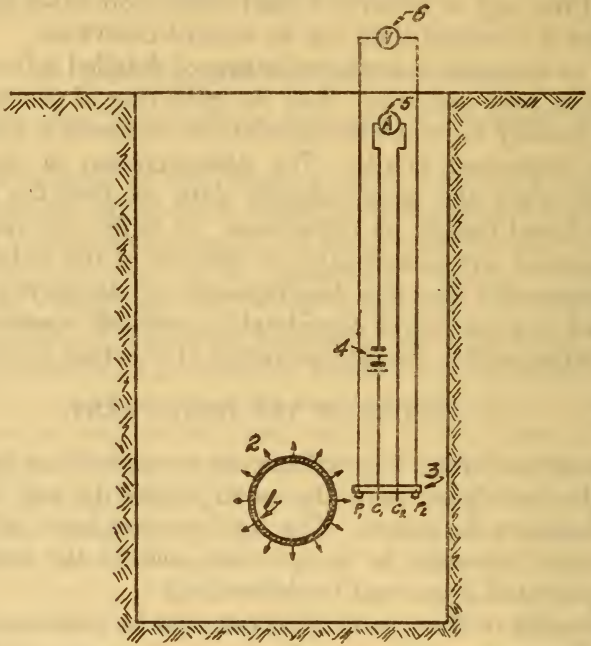

FIG. 1.—*Principles of earth-current meter*

1, pipe; 2, direction of current; 3, contactor; 4, battery; 5, ammeter; 6, voltmeter; P_1P_2, potential terminals; C_1C_2 current terminals

$$\theta_c = K\,E_c \tag{1}$$

where K is the constant of the voltage indicator, *6*, which includes the effect of the resistance in the leads and in the earth near the electrodes P_1 and P_2. This is sometimes an important consideration and will be discussed later. Further, it will be seen that E_c is proportional to the current I_c sent between the electrode C_1 and C_2 and to the resistivity r of the surrounding earth, or

$$E_c = \frac{I_c\,r}{A} \tag{2}$$

where A is a constant depending upon the geometrical arrangement of the group of electrodes. Substituting the value of E_c as given by equation (2), in equation (1) we have

$$\theta_c = \frac{K\,I_c\,r}{A} \tag{3}$$

In equations (2) and (3) it is assumed that the voltage drop between the electrodes P_1 and P_2 is caused solely by the current sent through the electrodes C_1 and C_2. In order that this may be true, conditions must be such that no other current flowing through the earth at the time measurement is made will in any way affect the apparatus. For the present we will assume that this is actually the case. It will be explained later how this is readily realized in practice.

After taking the above measurement of I_c and the corresponding E_c, the circuit of the battery, *4*, is opened, after which the voltage drop E_e between the voltage electrodes P_1 and P_2 will be solely due to the current which is flowing through the earth, or

$$E_e = i\,r\,L \tag{4}$$

where L is the distance between the electrodes P_1 and P_2, i is the mean current density in the region between the electrodes P_1 and P_2, and r, as above, is the resistivity of the earth in this region.

The corresponding deflection of the instrument, *6*, is θ_e, and we will then have

$$\theta_e = K\,E_e = K\,i\,r\,L \tag{5}$$

Dividing equation (3) by equation (5) we have

$$\frac{\theta_c}{\theta_e} = \frac{KE_c}{KE_e} = \frac{KI_cr}{KAirL} = \frac{I_c}{AiL} \tag{6}$$

Solving equation (6) for (i) we have

$$i = \frac{I_c\theta_e}{AL\theta_c} = \frac{I_cE_e}{ALE_c} \tag{7}$$

As stated above, A is a constant depending upon the geometrical form of the electrode group, P_1, C_1, C_2, and P_2. This can be determined once for all for a given contactor by immersing it in a medium, such as water, through which a current density of known value is sent. Under these circumstances, if we perform the two measurements indicated above and substitute the values in equation (7), i being in this case known, we can calculate the value of $\frac{1}{AL}$. When the distance L between the two electrodes P_1 and P_2 is known, the factor A can also be calculated. Calling the factor $\frac{1}{AL}$, for brevity, Q, we have

$$i = \frac{Q\theta_eI_c}{\theta_c} = \frac{QE_eI_c}{E_c} \tag{8}$$

In equation (8) i is the current per unit area, or the quantity which is to be measured, and Q is the known constant to be determined by calibration under known conditions.

In brief, therefore, to obtain the value of i we have to perform two operations. One is to send a known current I_c through the two electrodes C_1 and C_2, and at the same time to observe the corresponding deflection θ_c of the instrument, *6*, this being done in a manner described below, such that the instrument, *6*, will not be affected by any current other than that which flows from the battery, *4*, through the electrodes C_1 and C_2. The second is to disconnect the battery, *4*, and measure the deflection θ_e of the instrument, *6*, due solely to the earth current i. The three values θ_c, I_c, and θ_e are then substituted in equation (8) and the value of i calculated.

As stated above, the deflection of the voltage indicator, *6*, is affected by the resistance in series with its leads, and, therefore, by the resistance of the electrodes P_1 and P_2 and of the earth immediately surrounding them. In practice it is found that this resistance is often very high so that the instrument, *6*, may not give a true value of the voltage impressed in the earth between the two electrodes P_1 and P_2. It will be observed, however, from equation (6) that the resistivity r of the earth in the region in which the test is being made and also the constant K of the voltage indicator, *6*, disappear from the equation from which the earth current i is calculated. It will be seen, therefore, that in making this measurement neither the resistivity of the earth nor the true value of the voltage drop between the electrodes P_1 and P_2 need be known. This constitutes one of the important advantages of this method of measuring earth currents.

Equation (2) may be solved for r giving

$$r = A\frac{E_c}{I_c} \tag{9}$$

When the value of A has been determined for a contactor of any given size and form, the resistivity may readily be measured either by itself or as a by-product of the earth-current measurement.

It will be noted, however, that for the solution of equation (2) the true voltage drop between the potential electrodes P_1 and P_2 must be known and that the resistivity can, therefore, only be computed when the resistance in and adjacent to the electrodes is negligible. This condition can usually be secured by the proper choice of the voltmeter multiplier.

3. PRACTICAL EMBODIMENT OF THE PRINCIPLE

As stated previously, in obtaining readings with current flowing from battery, *4* (fig. 1), it is essential that some arrangement be provided whereby the deflection, θ_c, will be affected only by the current

I_c, which flows through the electrodes C_1 and C_2 and will not be influenced by any earth current already flowing. This can be accomplished in a very simple manner by an arrangement shown in Figure 2, which is a complete wiring diagram of the earth-current meter.

In this arrangement two commutators, *7* and *8*, mounted on the same shaft are employed. These commutators are so mounted that commutation takes place on both at substantially the same instant, and are provided with a crank whereby they may be rotated by hand at a suitable speed. The commutator, *7*, is interposed between the battery, *4*, and the current electrode terminals C_1 and C_2, while the commutator, *8*, is interposed between the potential electrode terminals P_1 and P_2 and the voltage indicator, *6*. The switch, *9*, is in the position shown by the dotted lines during this part of the test. It will be seen that an alternating current flows through the earth from the terminals C_1 and C_2 and impresses on the electrodes P_1 and P_2 an alternating voltage which is commutated simultaneously with the current through the electrodes C_1 and C_2 and gives rise to a unidirectional voltage on the voltage indicator, *6*. This instrument, being of the direct-current type, will, therefore, give a deflection θ_c proportional to the current I_c sent through the terminals C_1 and C_2. At the same time any unidirectional voltage impressed on the terminals P_1 and P_2 due to a stray earth current will be commutated so frequently that it will exercise no appreciable effect on the voltage indicator, and, hence, the reading of the latter will be just the same as if, for the time being, the earth current to be measured did not

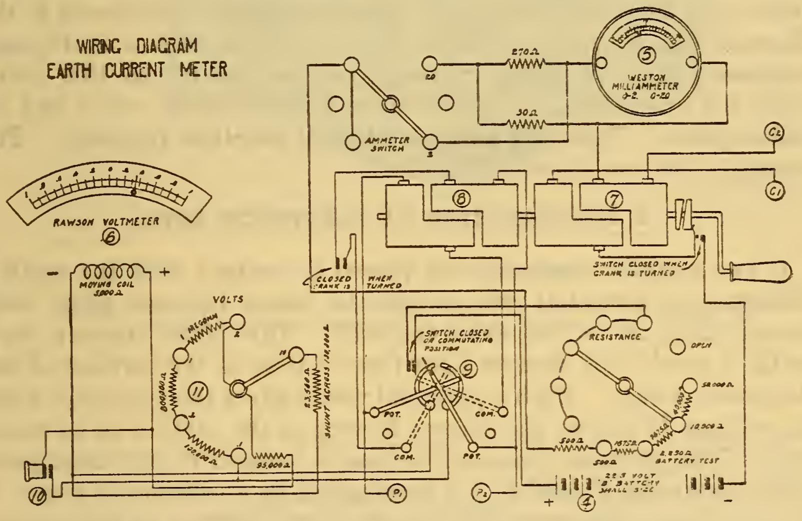

FIG. 2.—*Wiring diagram of earth-current meter*

4, battery; 5, milliammeter; 6, voltmeter; 7-8, commutators; 9, commutator switch; 10, short-circuiting switch; C_1C_2, current terminals; P_1P_2, potential terminals exist. After the measurements of the current I_c and the deflection θ_c are made under these conditions, the switch, *9*, is turned to the position shown by the solid lines, which, as will be seen from Figure 2, disconnects the battery, *4*, from the terminals C_1 and C_2 and at the same time eliminates the commutator, *8*, from the circuit between the terminals P_1 and P_2 and the voltage indicator, *6*, which latter is then read for the value θ_e. The three values θ_c, I_c, and θ_e are then substituted in equation (8) and the value of the earth current i calculated in any desired unit, depending on the value of the constant Q used.

The complete equipment for the measurement of earth currents comprises a test set and three sets of contactors. The test set contains the instruments and commutator arrangement described above and also the battery and other essentials. As shown in the diagram (fig. 2), the voltmeter, *6*, is provided with a multirange resistance unit, *11*, giving full-scale ranges from 0.1 to 10.0 volts, while the ammeter, *5*, is provided with two ranges, viz, 2 and 20 milliamperes. These are sufficient for all practical purposes. The complete test set is shown in Figure 3.

4. CONSTRUCTION OF ELECTRODE SETS

If two metallic electrodes are placed in contact with the earth a difference of potential will usually be found between them even though they are of the same material. This often amounts to a tenth of a volt and changes from time to time as the surfaces of the electrodes change. Such a potential would affect the voltmeter when the voltage E_e due to the current flowing in the earth is to be measured. This galvanic potential is greatly reduced if the metal parts of the electrodes P_1 and P_2 are surrounded by a solution of a salt of the metal from which they are constructed. So long as the solution remains clean and saturated the galvanic potential will be negligible. This construction also avoids polarization effects due to the flow of current through the galvanometer circuit, and for this reason electrodes so made are called nonpolarizable electrodes. The potential electrodes used with the earth-current meter are copper cups filled with copper sulphate, which is kept in place by means of wooden plugs. This reduces the galvanic potential to a few millivolts. Table 1 gives the variations in potential between such copper sulphate electrodes under several conditions. The data were taken at different times and the intervals in the first column are only approximate.

In column A the potential electrodes of a 4½-inch contactor were filled with a saturated solution of copper sulphate and left continuously under tap water. Column B represents a similar test of a 9-inch contactor.

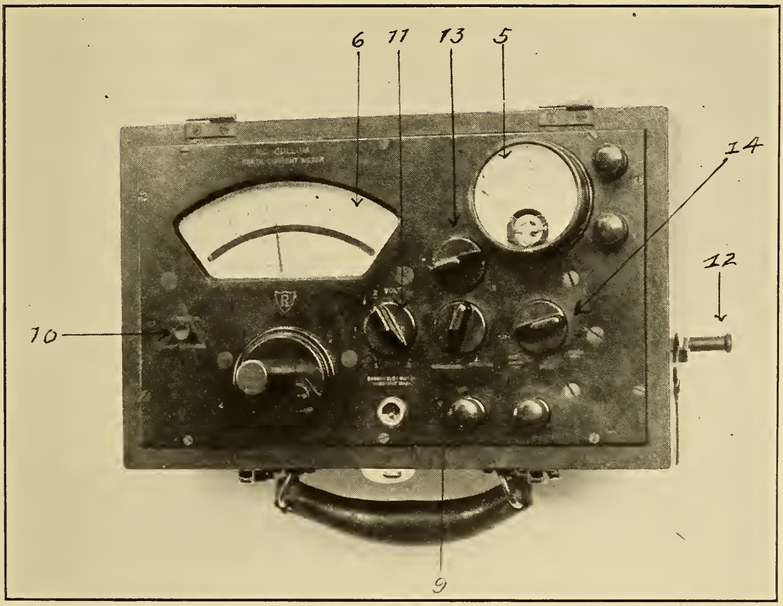

FIG. 3.—*Earth-current meter*

5, milliammeter; 6, voltmeter; 9, commutator switch; 10, short circuiting switch; 11, voltmeter switch; 12, commutator crank; 13, ammeter switch; 14, resistance switch

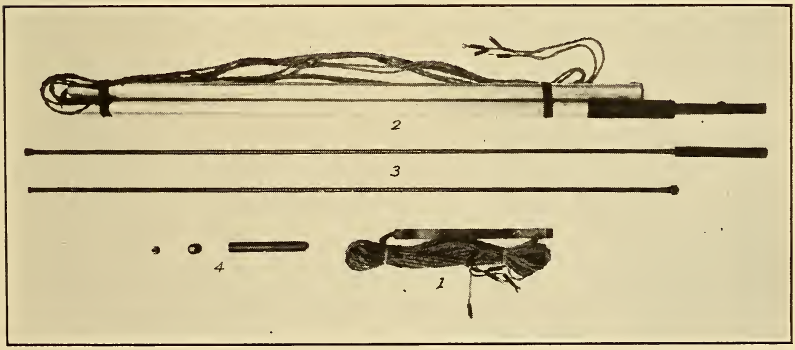

FIG. 4.—*Earth-current meter contactors*

1, trench contactor; 2, cantilever contactor; 3, single terminal electrode with extension rod; 4, single terminal electrode (disassembled)

Column C is a test similar to that of column B, except that powdered copper sulphate was added in the cups to keep the solution saturated.

Column D was obtained by reversing the caps on the contactor used for the "C" tests and repeating the tests in order to determine the effect of the wooden caps.

Column E was obtained where the same electrode was allowed to remain in the water only during the time when a reading was being obtained, thus reducing the rate of loss of copper sulphate from the cups. This condition approximates that to which the contactor would be subjected in actual practice.

The data indicate that the galvanic potentials are due to dilution of the copper sulphate, and that so long as the solution is clean and saturated the galvanic potential is small. Rather large galvanic potentials have sometimes resulted from the use of two caps of different kinds of wood, probably because the difference in their porosity causes unequal diffusion of the copper sulphate from the two electrodes. This condition should be avoided.

Table 1.—*Galvanic potential between electrodes*

Time from start		Millivolts between electrodes				
Hours.	Minutes	A	B	C	D	E
	0	−6.29	−1.0	0	−8.3	+0.9
	6	+1.26	+1.5	−2.4	−5.6	----------
	10	−.31	+2.4	−5.3	----------	+.4
	20	−3.77	+2.4	−9.2	−4.1	+.3
	40	−6.29	+3.4	----------	+.9	.0
	75	----------	+5.2	----------	+3.9	----------
2 to 3	----------	----------	----------	+14.5	+6.2	----------
5 to 7	----------	----------	+10.36	+13.9	+11.2	+2.5−0
20 to 26	----------	+7.85	----------	+16.4	+15.9	----------

Three types of contactor sets are shown in Figure 4. Type A shown as *1* is a "trench" contactor; *2* is a type B, or "cantilever" contactor, designed to be placed down in a small hole over a pipe; and *3* two separate nonpolarizable electrodes for exploring voltage conditions at various points in the earth where the other two types are not readily applicable.

Two sizes of the type A, or trench contactor, set are used as standard. The dimensions of these are shown in Figure 5, while Figures 6 and 7 show the construction, respectively, of the cantilever, or type B, electrode set, and of the exploring, or type C, electrode.

5. DETERMINATION OF CONSTANTS

In the discussion of the theory above, several constants have been introduced whose values depend upon the geometrical arrangement of the electrodes.

Since the values of these constants can be determined once for all for an electrode set of given type and size, it is not necessary for the user of the instrument to determine them, but a description of the method used and an account of this determination will throw some light on the characteristics of the electrodes and enable the reader better to understand their limitations.

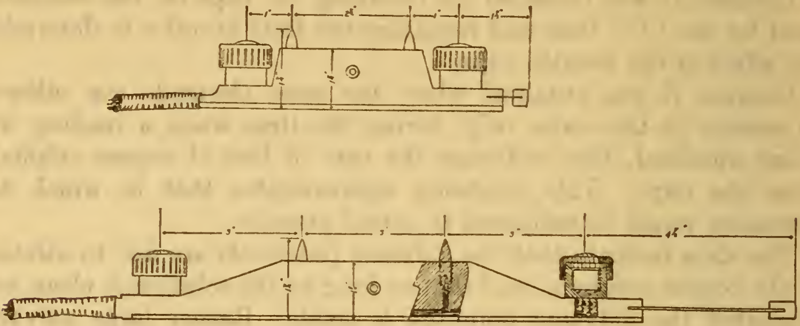

Fig. 5.—*Trench contactor construction*

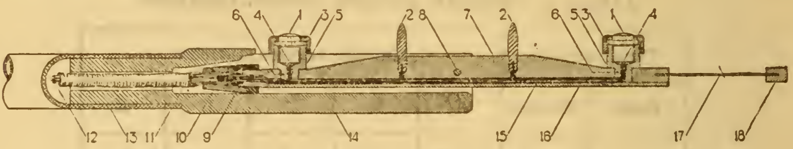

Fig. 6.—*Cantilever contactor construction*

1, wooden plug; 2, copper current terminal; 3, bakelite electrode cap; 4, copper electrode cup; 5, bakelite potential electrode; 6, threaded joint between electrode and cup; 7, bakelite electrode spacer; 8, steel rocker pin; 9, bakelite tube expander; 10, bakelite ferrule; 11, rubber tube; 12, rubber covered lead wires; 13, aluminum handle; 14, bakelite contactor fork; 15, asphalt filled lead channel; 16, bakelite contactor fork; 17, phosphor bronze spacer; 18, bakelite spacer terminal

Because it is not convenient in practice to give the contactors a simple geometrical form rendering their constants amenable to calculation, the constants must be determined by test. For this purpose a large rectangular tank (*1*, fig. 8), having insulating walls, is used. This tank is 4 feet wide, 2½ feet deep, and 5 feet long. At

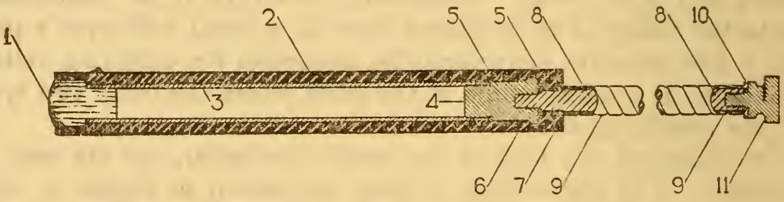

Fig. 7.—*Single terminal contactor construction*

1, wooden plug; 2, bakelite tube; 3, copper tube; 4, copper plug; 5, rubber gasket; 6, bakelite plug insulator; 7, bakelite rod insulator; 8, steel rod; 9, rubber tape rod insulator; 10, steel washer attached to rod; 11, copper binding post each end a sheet-metal electrode, *2*, is placed having an area equal to the cross section of the tank, namely, 4 by 2½ feet, or 10 square feet. If a current is passed between these electrodes when the tank is filled with water, there will be a practically uniform distribution of the current over the cross section of the tank.

The value of the current density or current per unit area can be determined by dividing the total current, as measured by an ammeter placed in the circuit, by the cross section of the water at right angles to the direction of current flow. If now we place at *3* a type A, or trench contactor, so that its terminals are in contact with the surface of the water and the line joining the several electrode terminals is parallel to the direction of current flow, we shall have a condition equivalent to that of practical use when the contactor is pressed against the wall of a trench, as previously described. The set-up for this test is also shown in Figure 8. If we now take the usual readings with the earth current meter, viz, E_e, E_c, and I_c, and substitute them in equation (8) above, the value of i being in this case known, we can calculate the value of Q for that particular type and size of contactor.

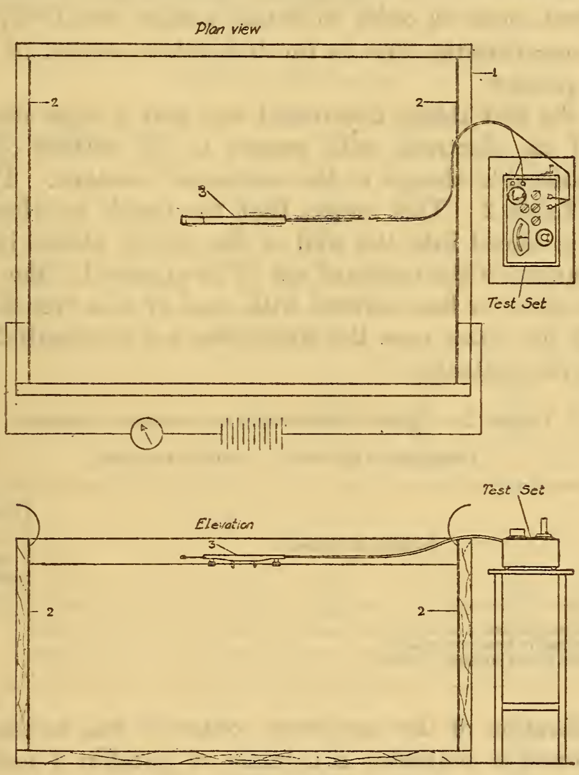

FIG. 8.—*Calibration tank*

1, tank; 2, copper plate; 3, contactor

The first attempts to determine Q with a direct current flowing between the plates of the tank gave irregular results, due to polarization at the plates and to the galvanic action between the potential electrodes when the gradient due to the leakage current was low. The galvanic potentials were entirely eliminated and the polarization effect much reduced by means of a double commutator similar to that used in the earth-current meter, one commutator being placed in the tank circuit and the other in the voltmeter circuit. A high-resistance galvanometer was substituted for the voltmeter of the earth-current meter in order to obtain greater sensitivity and eliminate any uncertainties due to the indefinite position of rest of the voltmeter pointer.

Among the first things discovered was that a slight change in the position of the electrode with respect to the surface of the water made a noticeable change in the contactor constant. This is illustrated in Table 2. This means that the depth to which a trench contactor is forced into the wall of the trench affects its constant. Similar changes in the constant are to be expected if the electrode is used when more or less covered with mud or in a trench filled with water. In the latter case the conditions are substantially those of the cantilever contactor.

TABLE 2.—*Effect of immersion on contactor constants*

[Electrodes in tap water. Average of four trials]

Position of electrode	Contactor constant	
	9-inch contactor	4½-inch contactor
Plugs ⅛ inch below surface	0.919	6.97
Terminals immersed to base of contactor	.824	----------
Electrode 6 inches below surface of water	.534	4.33

The calibration of the cantilever contactor was accomplished by casting around a contactor a cylinder of paraffin 3 feet long, 2½ inches in diameter, and so arranged that the current and potential terminals were exposed. The cylinder was then suspended horizontally in the tank parallel to the direction of flow of the current. The paraffin, being an insulator, had the same effect on the current distribution as a hole of the same dimensions.

Irregularities in the results first obtained made it seem desirable that the calibration should extend over the ranges of voltage, resistivity, and current density encountered in field work in order to determine whether the values obtained were dependent upon any of these factors. Tables 3, 4, 5, and 6 are the results of such a calibration. It will be noted that there is considerable variation in the values of the constant Q. The value, however, does not seem to depend on any of the variables tabulated and the variation appears to be due rather to unstable test conditions.

Among these uncontrolled conditions were slight leakage through the body of the tank, nonuniform discharge from the tank plates, nonuniform resistivity of the water due to polarization, convection, and changes in temperature, and variable amounts of moisture on the surface of the electrode. It is believed, however, that the average of the results obtained gives a value of the constant sufficiently accurate for all practical purposes.

TABLE 3.—*Calibration of 9-inch trench contactor*

IN FRESH WATER

i (milliamperes per square foot)	θ_o	θ_a	I_o	Q	r	$\frac{\theta_o}{I_o}$
	mv	*mv*	*ma*		*ohm-cm*	
0.1	9.69	23.90	0.27	0.913	3,940	88.5
0.5	58.55	57.65	.545	.905	4,760	105.8
5.0	704.6	490.4	3.73	.932	5,730	131.3
10.0	1,436.2	1,194.0	9.00	.924	5,840	132.6
Average				.919		

SALT ADDED

i (milliamperes per square foot)	θ_o	θ_a	I_o	Q	r	$\frac{\theta_o}{I_o}$
0.1	6.5	12.5	0.215	0.894	2,640	58.2
0.5	38.8	30.1	.44	.882	3,155	68.4
5.0	448.0	193.0	2.45	.880	3,640	78.8
10.0	904.0	340.0	4.20	.894	3,675	81.0
Average				.887		

MORE SALT ADDED

i (milliamperes per square foot)	θ_o	θ_a	I_o	Q	r	$\frac{\theta_o}{I_o}$
0.1	4.7	8.15	0.20	0.867	1,910	40.7
0.5	26.4	23.8	.515	.875	2,140	46.2
5.0	294.0	163.0	3.10	.894	2,390	52.6
10.0	596.0	247.0	4.75	.872	2,420	52.0
Average				.877		

MORE SALT ADDED

i (milliamperes per square foot)	θ_o	θ_a	I_o	Q	r	$\frac{\theta_o}{I_o}$
10	18.9	12.8	8.0	0.846	76.8	1.60
50	102.0	84.0	47.5	.866	83.0	1.77
100	210.0	260.0	155.0	.800	85.3	1.68
Average				.837		

MEASUREMENT REPEATED WITH DIFFERENT GALVANOMETER MULTIPLIER

i (milliamperes per square foot)	θ_o	θ_a	I_o	Q	r	$\frac{\theta_o}{I_o}$
10	19.1	22.0	14.5	0.795	77.5	1.51
20	35.6	22.0	14.5	.852	72.4	1.51
40	77.6	45.8	27.5	.859	78.8	1.67
50	96.7	45.8	27.25	.868	78.6	1.68
Average				.843		

TABLE 3.—*Calibration of 9-inch trench contactor*—Continued

MEASUREMENT REPEATED NEXT DAY

i (milliamperes per square foot)	θ_e	θ_c	I_c	Q	r	$\frac{\theta_c}{I_c}$
	mv	*mv*	*ma*		*ohm-cm.*	
3	5.6	11.0	7.0	0.843	75.8	1.57
30	58.0	45.8	28.0	.847	78.6	1.63
60	120.0	240.0	145.0	.828	81.1	1.66
Average				.839		

SALT ADDED

i (milliamperes per square foot)	θ_e	θ_c	I_c	Q	r	$\frac{\theta_c}{I_c}$
3	4.5	11.0	8.35	0.879	61.0	1.32
30	46.8	22.9	17.0	.864	63.4	1.35
60	102.0	90.0	60.0	.882	69.1	1.50
Average				.875		

REPEATED TESTS ABOVE

i (milliamperes per square foot)	θ_e	θ_c	I_c	Q	r	$\frac{\theta_c}{I_c}$
3	4.5	22.0	17.0	0.862	61.0	1.29
15	21.0	22.0	17.0	.924	56.9	1.29
30	46.3	45.8	32.5	.913	62.7	1.41
60	96.0	240.0	170.0	.883	65.0	1.41
100	166.0	247.0	170.0	.876	67.4	1.45
Average				.891		
General average				.874		

TABLE 4.—*Calibration of 4½-inch trench contactor*

IN FRESH WATER

i (milliamperes per square foot)	θ_e	θ_c	I_c	Q	r	$\frac{\theta_c}{I_c}$
	mv	*mv*	*ma*		*ohm-cm.*	
0.1	4.6	28.4	0.085	7.26	3,740	334
.5	27.2	46.6	.127	6.74	4,430	367
5.0	322.0	390.0	.850	7.12	5,240	459
10.0	644.0	654.0	1.50	6.77	5,240	436
Average				6.97		

SALT ADDED

i (milliamperes per square foot)	θ_e	θ_c	I_c	Q	r	$\frac{\theta_c}{I_c}$
0.1	2.97	22.2	0.105	7.12	2,412	211
0.5	18.6	55.2	.215	6.90	3,030	256
5.0	220.0	790.0	2.50	7.18	3,580	316
10.0	450.0	676.0	2.5	6.97	3,656	314
Average				7.04		

MORE SALT ADDED

i (milliamperes per square foot)	θ_e	θ_c	I_c	Q	r	$\frac{\theta_c}{I_c}$
0.1	2.4	28.4	0.18	6.58	1,950	158
0.5	14.3	40.0	.22	6.36	2,330	182
5.0	144.0	626.0	3.10	7.02	2,340	202
10.0	294.0	684.0	3.35	6.95	2,390	204
Average				6.73		

MORE SALT ADDED

i (milliamperes per square foot)	θ_e	θ_c	I_c	Q	r	$\frac{\theta_c}{I_c}$
10	8.2	26.4	5.0	6.44	666	5.28
50	50.0	330.0	47.5	6.95	813	6.95
100	106.0	336.0	50.0	6.34	862	6.72
Average				6.58		

TABLE 4.—*Calibration of 4½-inch trench contactor*—Continued

TEST REPEATED

i (milliamperes per square foot)	θ_e	θ_c	I_c	Q	r	$\frac{\theta_c}{I_c}$
10	8.3	22.0	4.2	6.32	674	5.24
20	15.4	22.0	4.2	6.80	626	5.24
40	36.2	45.8	7.7	6.58	736	5.95
60	45.8	45.8	7.7	6.49	744	5.95
Average				6.55		
TEST REPEATED NEXT DAY						
3	2.7	22.0	3.7	6.61	731	5.94
30	29.0	45.8	7.35	6.45	713	6.23
60	60.0	600.0	87.5	6.86	785	6.86
Average				6.64		
TEST REPEATED						
3	2.2	22.0	4.45	6.74	495	4.94
30	23.4	45.8	8.60	6.83	634	5.32
60	54.0	368.0	64.0	6.38	732	5.75
Average				6.65		
TEST REPEATED						
3	2.1	22.0	4.6	6.83	569	4.78
15	10.0	22.0	4.55	7.25	542	4.83
30	22.9	45.8	8.7	6.90	622	5.26
60	48.0	600.0	110.0	6.82	650	5.45
100	80.0	600.0	110.0	6.82	650	5.45
Average				6.92		
General average				6.78		

TABLE 5.—*Calibration of 9-inch cantilever contactor*

IN SALT WATER

i (milliamperes per square foot)	θ_e	θ_c	I_c	Q	r	$\frac{\theta_c}{I_c}$
	mv	*mv*	*ma*		*ohm-cm*	
10	10.8	22	33.5	0.608	43.8	0.656
30	31.9	22	34.0	.609	43.2	.647
100	168.0	156	160.0	.580	68.1	.975
Average				.599		
10	9.5	22	36.0	.644	38.6	.611
30	29.9	22	38.0	.582	40.5	.579
100	168.0	164	170.0	.574	68.1	.964
Average				.600		
SALT WATER DILUTED ABOUT ONE-HALF						
10	20.0	22.0	18.5	0.595	81.3	1.19
30	75.6	45.8	30.0	.606	102.4	1.53
100	324.0	166.0	90.0	.570	131.6	1.84
Average				.590		
TANK REFILLED WITH FRESH WATER						
0.1	7.0	20.8	0.45	0.660	2,844	46.2
0.5	43.2	22.8	0.415	.636	3,510	54.9
1.0	106.0	30.0	0.455	.622	4,310	65.9
5.0	512.0	102.0	1.55	.642	4,160	65.8
10.0	1,037.5	172.0	2.60	.637	4,210	66.1
Average				.639		
General average				.612		

TABLE 6.—*Calibration of 4½-inch cantilever contactor*

i (milliamperes per square foot)	θ_c	θ_o	I_c	Q	r	$\frac{\theta_c}{I_c}$
IN SALT WATER						
	mv	*mv*	*ma*		*ohm-cm*	
10	5.7	22	6.02	6.42	46.3	3.65
30	17.6	22	6.00	6.25	47.7	3.67
100	84.0	300	58.00	6.16	68.3	5.17
Average				6.28		
10	5.7	22	5.8	6.66	46.3	3.79
30	19.4	22	6.05	5.65	52.6	3.64
100	84.0	600	125.0	5.71	68.3	4.80
Average				6.01		
SALT WATER DILUTED ABOUT ONE-HALF						
10	12.8	22.0	2.95	5.83	104.0	7.46
30	43.8	45.8	5.35	5.87	118.7	8.56
100	168.0	600.0	62.0	5.76	136.5	9.68
Average				5.82		
TANK REFILLED WITH FRESH WATER						
0.1	2.86	22.0	0.12	6.41	2,323	183
0.5	19.7	60.2	.24	6.37	3,200	251
1.0	51.2	148.0	.445	6.50	4,160	333
5.0	256.0	518.0	1.60	6.32	4,160	324
10.0	524.0	600.0	1.85	6.19	4,260	324
Average				6.36		
General average				6.15		

The resistivities of the tank water given in the sixth column are computed from the current flowing between the plates and the voltage drop between the potential terminals of the contactors. It will be noted that in nearly all cases these resistivities increase with the current densities given in column 1. The resistivity can also be calculated from equation (3), $\theta_c = \frac{KI_c\, r}{A}$, in which A and K are constants, which makes r proportional to $\frac{\theta_c}{I_c}$. The values of this ratio are given in column 7, which indicates the same sort of changes in resistivity. Tables 3, 4, 5, and 6 indicate that the constant of the electrode is not affected by the intensity of the leakage current, the amount of test current, or the soil resistivity. This is, of course, to be inferred from equation (8). Nevertheless, some readers may be interested in the extent to which the tests confirm the theory presented.

In practice, higher resistivities will sometimes be encountered than could be readily obtained in the laboratory. Under such conditions the leakage currents are usually unimportant, or, if of sufficient intensity to cause serious corrosion, result in such earth gradients as are very favorable to earth-current testing, and the tables indicate that little would be gained by using an electrolyte of higher resistivity.

It will be observed that the value of Q determined as above described applies only to the case of parallel lines of current flow. This condition sometimes occurs in practice when measuring earth currents at points remote from buried pipes. However, the most common case is that in which the current is measured at points where it is flowing radially outward from a pipe, and hence the stream lines are diverging rapidly, giving rise to progressively varying current densities at varying distances from the pipe. Furthermore, in this case it is desired to know not the current density in the region between the ends of the contactor but the current density at the pipe surface. A factor R to be used in equation (8) instead of Q, so as to give the current density at the pipe surface under specified conditions, can readily be calculated if the value of Q has once been determined by the method described above. The equation for the current at the surface of the pipe is then

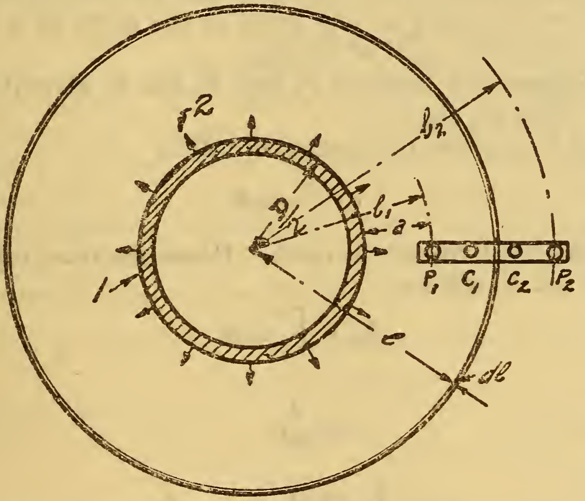

FIG. 9.—*Determination of current density at pipe surface*

1, outside of pipe; 2, direction of current; $\frac{D_1}{2}$ outside radius of pipe; a, distance between P_1 and outside of pipe; l, distance from center of pipe to element of soil dl; l_1, distance from center of pipe to P_1; l_2, distance from center of pipe to P_2; P_1P_2, potential terminals; C_1C_2, current terminals

$$i=\frac{RE_e'I_c}{E_c} \qquad (10)$$

The value of R is derived as follows:

Referring to Figure 9, suppose the pipe, *1*, to be discharging current radially in all directions as shown by the arrows, *2*. The contactor, P_1, C_1, C_2, P_2, is placed near the pipe and extending radially from it, the nearest electrode P_1 being at a distance a from the pipe surface and the outer electrode being at a distance $a+L$, L being the distance between P_1 and P_2, which is fixed for any given electrode group. The outside radius of the pipe is $\frac{D}{2}$ as shown.

Let I = current discharge per unit length of pipe,

i = current density or current per unit area at the pipe surface,

i_s = current density at any point in the earth at a distance l from the center of the pipe,

E_e' = voltage drop between P_1 and P_2 due to current discharge from the pipe.

The voltage drop across the element dl will be

$$dE_e' = ri_s dl \tag{11}$$

where r is the resistivity of the earth. Hence the total voltage drop between P_1 and P_2 will be

$$E_e' = \int_{l_1}^{l_2} i_s r dl \tag{12}$$

Since

$$i_s = \frac{I}{2\pi l}$$

$$E_e' = \frac{Ir}{2\pi}\int_{l_1}^{l_2}\frac{dl}{l} = \frac{Ir}{2\pi}\log_e\frac{l_2}{l_1} \tag{13}$$

Also, since i, the current density at the pipe surface, is equal to $\frac{I}{\pi D}$ equation (13) becomes

$$E_e' = \frac{irD}{2}\log_e\frac{l_2}{l_1} \tag{14}$$

Further, since

$$l_1 = \frac{D}{2} + a$$

and

$$l_2 = l_1 + L = \frac{D}{2} + a + L$$

we have

$$E_e' = \frac{irD}{2}\log_e\left(1 + \frac{2L}{D+2a}\right) \tag{15}$$

For the case of parallel stream lines we have from equation (4)$E_e = irL$. Hence, from equations (8), (10), and (15) we obtain

$$\frac{E_e'}{E_e} = \frac{D}{2L} \log_e \left(1 + \frac{2L}{D+2a}\right) = \frac{Q}{R}$$

$$R = \frac{2QL}{D \log_e \left(1 + \frac{2L}{D+2a}\right)} = \frac{2QL}{2.303\ D \log_{10} \left(1 + \frac{2L}{D+2a}\right)} \qquad (16)$$

It will be seen from equation (16) that in measuring the current discharged from a pipe the constant R involves not only the constant Q, which applies in the case of parallel stream lines, but involves also the outside diameter D of the pipe, the distance L between the electrodes P_1 and P_2, and the distance a between the nearest electrode and the pipe surface. The spacers provided on the ends of the contactor serve to fix this distance a. The value of Q having been determined for parallel stream-line flow by tests in a suitable tank, as described above, the value of R can be calculated from equation (16) for any particular values of the constants involved and for any pipe diameter. Values of R for the standard contactors and more common sizes of pipe are given in Tables 7 and 8.

TABLE 7.—"*R*" *for determining leakage from pipe surface under various condition*

[Class B cast-iron pipe sizes]

Nominal size of pipe (inches)	R for 4½-inch contactor			R for 9-inch contactor		
	Trench, dry	Cantilever contactor		Trench, dry	Cantilever contactor	
		2½-inch hole, dry	In water		2½-inch hole, dry	In water
	$Q=6.78$	$Q=6.15$	$Q=4.50$	$Q=0.874$	$Q=0.612$	$Q=0.543$
3	18.6	16.8	12.3	4.56	3.19	2.83
4	16.2	14.7	10.6	3.80	2.66	2.36
6	13.5	12.2	9.0	2.95	2.07	1.83
8	12.1	11.0	8.0	2.51	1.76	1.56
10	11.1	10.1	7.4	2.21	1.55	1.37
12	10.5	9.5	6.9	2.01	1.40	1.25
14	10.0	9.0	6.6	1.85	1.30	1.15
16	9.6	8.7	6.4	1.74	1.22	1.08
18	9.3	8.4	6.2	1.65	1.15	1.02
20	9.1	8.2	6.0	1.57	1.10	.98
24	8.7	7.9	5.8	1.46	1.02	.91
30	8.3	7.6	5.5	1.35	.95	.84
36	8.1	7.3	5.4	1.27	.89	.79
42	7.9	7.2	5.3	1.22	.85	.76
48	7.8	7.1	5.2	1.18	.82	.73
54	7.6	6.9	5.1	1.14	.80	.71

These constants are computed on the basis of $a=1.5$ for the 4½-inch contactor and $a=4.5$ for the 9-inch contactor. See formula page 700. Units are so chosen as to give current density in milliamperes per square foot when the current I_o (equation (10)) is measured in milliamperes.

TABLE 8.—"*R*" *for determining leakage from pipe surface under various conditions*

[Steel pipe sizes]

Nominal size of pipe (inches)	R for 4½-inch contactor			R for 9-inch contactor		
	Trench, dry	Cantilever contactor		Trench, dry	Cantilever contactor	
		2½-inch hole, dry	In water		2½-inch hole, dry	In water
	$Q=6.78$	$Q=6.15$	$Q=4.50$	$Q=0.874$	$Q=0.612$	$Q=0.543$
¾	49.7	45.0	33.0	14.6	10.2	9.6
1	41.2	37.3	27.3	11.8	8.3	7.4
1¼	34.2	31.0	22.7	9.6	6.7	6.0
1½	30.8	27.9	20.4	8.5	5.9	5.3
2	26.1	23.7	17.3	7.0	4.9	4.3
2½	22.8	20.7	15.2	5.9	4.2	3.7
3	20.1	18.2	13.3	5.0	3.5	3.1
3½	18.5	16.7	12.3	4.5	3.2	2.8
4	17.2	15.6	11.4	4.1	2.9	2.6
4½	16.2	14.7	10.8	3.8	2.7	2.4
5	15.3	13.9	10.1	3.5	2.5	2.2
6	14.0	12.7	9.3	3.1	2.2	1.9

These constants are computed on the basis of $a=1.5$ for the 4½-inch contactor and $a=4.5$ for the 9-inch contactor. See formula page 700. Units are so chosen as to give current density in milliamperes per square foot when the current I_o (equation (10)) is measured in milliamperes.

6. EFFECT OF NEIGHBORING PIPES ON MEASUREMENTS

A study of equation (10) indicates that it contains two factors, one, E'_e, due to an earth gradient and the other, $\frac{I_c}{E_c}$, due to the earth resistivity. The change in gradient with distance from the center of the pipe against which the electrode is placed and from which the current is assumed to come is taken care of in the constant R as shown in the derivation of equation (16). The factor $\frac{I_c}{E_c}$ is identical with the same factor in equation (8) which is developed on the assumption of uniform resistivity throughout the region affected by the current used in obtaining the value of this ratio. The contactor is used, however, in the neighborhood of a pipe and frequently not far from other pipes. It is pertinent, therefore, to inquire as to the minimum separation between the contactor and the pipe in order that the pipe have no effect on the resistance measurement. To determine this for an extreme condition a 16-inch steel pipe was half immersed in salt water and the deflection θ_c determined for various positions of the contactor with respect to the pipe, I_c being kept constant.

Table 9 shows the results of this test. The galvanometer constants were different in the different tests, and θ_c was somewhat affected by slight differences in depth to which the contactors were immersed.

The data for the 9-inch contactor indicates that P_1 should not be nearer than 4 inches from a pipe to which the contactor is perpendicular. It is on this account that the contactor was provided with a 4½-inch spacer. It will be noticed that the deflection θ_c is only slightly affected by a parallel pipe 4 inches to one side or 8 inches beneath the contactor. These figures, therefore, roughly outline the portion of earth which is involved in an earth-current measurement.

TABLE 9.—*Effect of pipes on operation of contactors*

[$\frac{\theta_0}{I_0}$ for electrodes on surface of salt water r=about 50 ohm-centimeters]

9-INCH TRENCH CONTACTOR

Distance of potential terminal P_1 from surface of pipe in inches	Pipe half immersed				6-inch cast-iron pipe under and parallel to contactor
	Contactor perpendicular to pipe		Contactor parallel to pipe		
	16-inch steel pipe	6-inch cast-iron pipe	16-inch steel pipe	6-inch cast-iron pipe	
½				133	
1	45	666		333	8
1½					37
2	46	766	40	533	77
3	47	800	44. 5	600	125
4	47. 5	800	46	666	149
5	48	800	47	666	162
6	48		48		167
8	48	800	48		172
9				666	172. 5
10					173
12		800		666	175

4½-INCH TRENCH CONTACTOR

Distance of potential terminal P_1 from surface of pipe in inches	16-inch steel pipe, perpendicular	6-inch cast-iron pipe, perpendicular	16-inch steel pipe, parallel	6-inch cast-iron pipe, parallel	6-inch cast-iron pipe under and parallel to contactor
½		280		227	
1	107	300		260	35. 5
2	107	300		280	112
2½			107		
3	107	300	107	286	129
4			107	293	136
5	107	303		293	137
6			107	293	137
8	107		107	293	137
10				293	137
12		307		293	137

The 4½-inch contactor is constructed with the potential terminals relatively nearer the current terminals, and on this account is less influenced by pipes in the neighborhood. The limiting distance of a pipe to which the 4½-inch contactor is perpendicular is seen to be less than an inch and the minimum permissible distance for a parallel pipe is between 3 and 5 inches.

Roughly speaking, we may say that the earth resistivity measurement when made with a 9-inch contactor involves a semiovoid approximately 17 inches long with a 4-inch minor and an 8-inch major radius at the center. The 4½-inch contactor involves a similar volume 7 inches long with maximum radii of 1 inch and 3 inches.

II. PROCEDURE IN USING THE EARTH-CURRENT METER

1. MEASUREMENT OF EARTH CURRENTS WITH TRENCH CONTACTOR

The two nonpolarizable electrodes at the extreme ends of the four-terminal contactor should be filled with copper sulphate prior to starting the day's work. The instrument is then ready for any of the several classes of measurements to which it is adapted. These comprise (1) the measurement of earth currents, (2) the determination of the polarity of a pipe with respect to earth, and (3) the measurement of the resistivity of the earth. The last two are but special phases of the first, and if the earth current is measured both the polarity of the pipe and the resistivity of the earth are determinable from a single set of data.

In general, in using the earth-current meter it is preferable to make the tests in an open trench, the contactor being placed in the wall of the trench and on a line extending radially from the pipe. Special cases arise where such an excavation is not necessary and this will be referred to later, but wherever practicable a small excavation should be made over the pipe. The following explanation of procedure is based on the assumption that the instrument is used in this way:

The type A, or trench, contactor (*1*, fig. 4, and fig. 5) is placed against the wall of the trench as shown in Figure 10 on a line extending radially from the pipe in whichever direction it is desired to measure the current discharge, and as close to it as the spacer of the end of the contactor will permit. It should be firmly pressed against the trench wall either by an attendant or preferably by securing it with some convenient form of brace. The leads should be connected to the test set after the manner indicated by the letters on the terminal, those marked P_1 and P_2, and C_1 and C_2, being connected to binding posts bearing similar notations. The test set should be made approximately level, as indicated by the small level mounted on its face.

The contactor having been put in place and the leads properly connected to the test set as described above, the switch, *9* (fig. 3), is turned to the point marked "Commutator," the rheostat, *14*, turned to put all of the resistance into the ammeter circuit, and the voltmeter dial, *6*, set on the 1-volt range. The folding crank at the right of the case, shown by the arrow *12*, is opened out and turned at the rate of about one or two revolutions per second. The rate can be varied throughout wide limits without affecting the accuracy of the measurements. This rotates the commutator and also automatically closes the battery circuit through the operation of the automatic switches actuated by the commutator shaft, as shown in the wiring diagram in Figure 2. If all four terminals are in contact with the

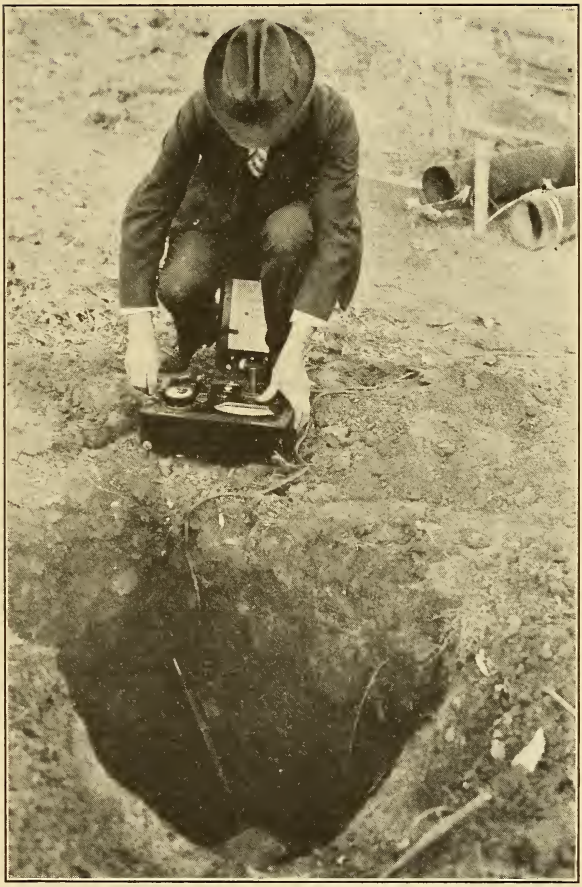

Fig. 10.—*Use of trench contactor*

earth, both instruments of the test will show positive deflections. A negative reading on the voltmeter indicates that an error has been made in connecting either the current or potential terminals which should be corrected. If the voltmeter does not show a deflection, one or more terminals of the contactor do not touch the earth. This can be remedied by pressing the contactor more firmly against the earth or making a slight change in its position. Except where very rough or rocky surfaces are encountered there will be little trouble due to electrode contacts.

The purpose of this preliminary test is to determine whether all of the terminals are making contact with the soil. When this condition has been attained, the switch, *9*, is turned to the position marked "Potential" and the switch, *11*, adjusted to secure a deflection of the voltmeter of suitable magnitude for accurate readings.

As with other instruments, it is, of course, desirable to choose such a scale or multiplier as will give a large deflection of the pointer. When this is done with the earth-current meter, a source of error may be introduced which is often disregarded in voltage measurements, although the phenomenon involved is not peculiar to the earth-current meter and, indeed, would be much more noticeable if an ordinary voltmeter were substituted for it. Any voltmeter indicates the voltage maintained between its terminals, while the voltage desired is that which exists before the connection is made between the two points to which these terminals are connected. If there is a resistance in the circuit between the instrument and the source of potential, the voltage is distributed between the instrument and the external circuit in proportion to their resistances. Thus, if the voltmeter has a resistance of 1,000 ohms and the external circuit an equal resistance, the voltmeter will indicate but half the total voltage. If the resistance of the voltmeter is doubled, it will indicate two-thirds of the total voltage.

When two terminals are placed in the earth for the purpose of obtaining the voltage between them, there is always involved a contact resistance, and frequently this resistance is of the order of several hundred ohms. On this account a low-resistance voltmeter would not indicate the true potential between the terminals; the earth-current meter voltmeter has, therefore, been constructed with a very high resistance to minimize the error. It is rarely noticeable on the 1-volt scale, which involves an instrument resistance of a megohm and is only of importance when the 0.1-volt scale is used with the electrodes in dry ground or where the contact is poor for some other reason. Nevertheless it is always best to try two scales of the voltmeter. If both give the same result, the exterior resistance is negligible. If the readings differ appreciably, the higher resistance scale must be used, even though the deflection is much smaller. As the high resistance may be due to a potential electrode being out of copper sulphate, resting on a stone or in poor contact with the earth, these possibilities should be considered before the proper scale is decided upon.

The most suitable voltmeter scale having been chosen, the switch, *9*, is returned to the commutator position, and while turning the crank the resistance in the ammeter circuit is adjusted until suitable deflections are obtained on both the ammeter and the voltmeter. If possible, this condition should be secured without changing the voltmeter resistance. If it is not possible to secure sufficiently large readings on both instruments without a readjustment of the voltmeter multiplier, turn the switch, *11*, to the potential position and repeat the measurements as before. It is very desirable to have the same voltmeter multiplier for both the readings of the voltmeter, as this eliminates any errors due to resistance in the electrode terminals themselves. However, this precaution is of importance, as a rule, only where soil resistances are very low. If it is necessary to use a lower range of the voltmeter in making the potential tests than is used in making the current tests, the magnitude of the error and the proper correction therefor can be determined by making the potential readings with two different settings of the voltmeter multiplier, as, for instance, on the 0.1-volt range and the 0.2-volt range. If the reading in volts on the 0.1 range is materially smaller than on the 0.2 range, the need of a correction is indicated, the amount of which can readily be calculated from the two readings.

When the instrument has been adjusted to give suitable deflections with the switch, *9*, in either position, readings of both the ammeter and voltmeter are taken while turning the crank. These readings are recorded, the current being designated as I_c or commutated current and the voltage as E_c or commutated voltage. Then the switch, *9*, is shifted to the potential position and the voltmeter readings taken at regular intervals for a sufficient length of time to give representative results for that locality. The time necessary will depend on the car schedules and various other local conditions and must be determined by the engineer in charge. Usually from 5 to 15 minutes will suffice. This voltage, due to the current discharge from pipe to earth, is recorded as E_e. After the voltage reading has been taken, it is well to repeat the commutator readings to determine whether there has been any change in the condition of the electrode during the test. This additional reading requires so little time that it is more than justified by the extra assurance which it affords.

Figures 11 and 12 show convenient forms for recording earth current observations.[1] It is advisable not to attempt to reduce the individual readings of the voltmeter to volts by application of the multiplier, as this may lead to confusion. It is best to record directly on the data sheet the actual deflections θ_e and θ_c as percentages of full-scale deflection. The setting, *M*, of the multiplier switch should also be recorded at the beginning of the observation of both θ_e and θ_c, as it will be necessary to reduce these deflections to volts

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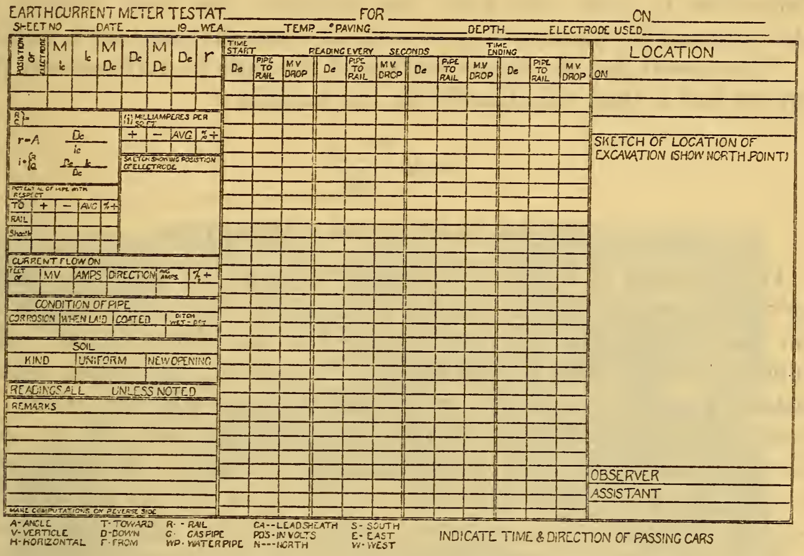
[1] These forms were developed by K. G. Kellogg, consulting electrolysis engineer.


EARTH CURRENT METER TEST AT ____ FOR ____ ON ____
SHEET NO ____ DATE ____ 19__ WEA. ____ TEMP ____ ° PAVING ____ DEPTH ____ ELECTRODE USED ____

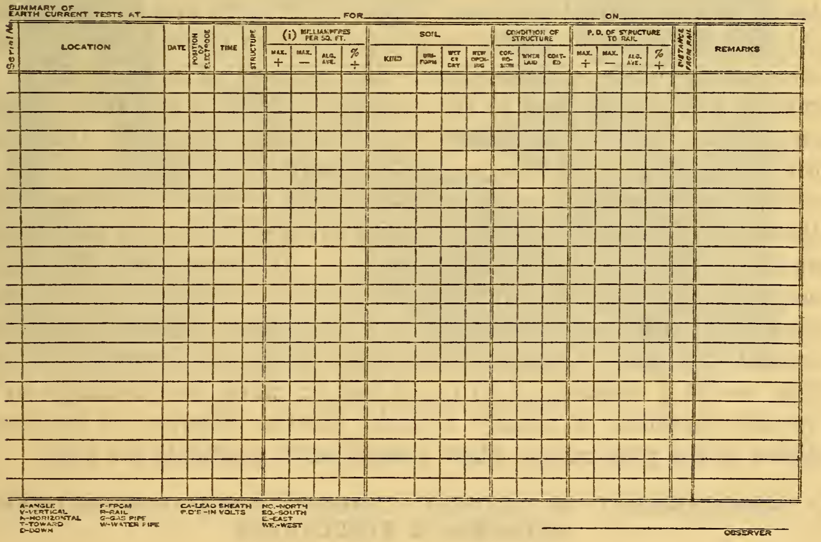
POSITION OF ELECTRODE | M ic | Ic | M Dc | Dc | M De | De | r
R/C =
r = A Dc/ic
i = R/A Dc Ic/Dc
(i) MILLIAMPERES PER SQ. FT.: + | − | AVG | % +
SKETCH SHOWING POSITION OF ELECTRODE
POTENTIAL OF PIPE WITH RESPECT TO: + | − | AVG | % +
RAIL
Sheath
CURRENT FLOW ON
TEST OF | MV | AMPS | DIRECTION | AVG AMPS | % +
CONDITION OF PIPE
CORROSION | WHEN LAID | COATED | DITCH WET - DRY
SOIL
KIND | UNIFORM | NEW OPENING
READINGS ALL UNLESS NOTED
REMARKS
MAKE COMPUTATIONS ON REVERSE SIDE

TIME START | READING EVERY SECONDS | TIME ENDING
De | PIPE TO RAIL | MV DROP | De | PIPE TO RAIL | MV DROP | De | PIPE TO RAIL | MV DROP | De | PIPE TO RAIL | MV DROP

LOCATION
ON
SKETCH OF LOCATION OF EXCAVATION (SHOW NORTH POINT)
OBSERVER
ASSISTANT

A - ANGLE
V - VERTICLE
H - HORIZONTAL
T - TOWARD
D - DOWN
F - FROM
R - RAIL
G - GAS PIPE
WP - WATER PIPE
CA - LEAD SHEATH
POS - IN VOLTS
N - NORTH
S - SOUTH
E - EAST
W - WEST
INDICATE TIME & DIRECTION OF PASSING CARS

FIG. 11.—*Detail data sheet*


SUMMARY OF EARTH CURRENT TESTS AT ____ FOR ____ ON ____

Serial No.	LOCATION	DATE	POSITION OF ELECTRODE	TIME	STRUCTURE	(i) MILLIAMPERES PER SQ. FT.				SOIL				CONDITION OF STRUCTURE			P. D. OF STRUCTURE TO RAIL				DISTANCE FROM RAIL	REMARKS
						MAX. +	MAX. −	ALG. AVE.	% +	KIND	UNI-FORM	WET OR DRY	NEW OPEN-ING	COR-RO-SION	WHEN LAID	COAT-ED	MAX. +	MAX. −	ALG. AVE.	% +		

A-ANGLE
V-VERTICAL
H-HORIZONTAL
T-TOWARD
D-DOWN
F-FROM
R-RAIL
G-GAS PIPE
W-WATER PIPE
CA-LEAD SHEATH
P.D'S -IN VOLTS
NO.-NORTH
SO.-SOUTH
E.-EAST
WE.-WEST
OBSERVER

FIG. 12.—*Summary data sheet*

if the multipliers are different for the two readings or if the earth resistivity is to be calculated. In calculating the value of the leakage current i, it is of course necessary to reduce the observed deflections to volts only when the multiplier has been changed in the course of the observations or when it is not the same for θ_e and θ_c.

The current density at the surface of the pipe in milliamperes per square foot is then calculated from the formula

$$i=R\frac{E'_e\ I_c}{E_c}$$

2. USE OF CANTILEVER CONTACTOR

For this type of contactor, designed to be placed down in a small hole, as shown in Figure 13, the value of R to be used depends on the size of the hole and also on whether the hole contains water sufficient to immerse the contactor. In use, the electrodes should either be entirely above the water line or completely immersed. A hole about 2½ inches in diameter is commonly used. If the cantilever contactor is used for determining the vertical discharge from a pipe, the hole should be over the center of the pipe, otherwise only the vertical component of the radial discharge will be measured.

Experience shows this measurement of the current density in a vertical direction upward from the pipe to be sufficient when the tested pipe is several feet from other conductors, and in such cases the type B contactor placed in a 2½-inch hole affords a simple and inexpensive mode of procedure. If, however, a pipe parallels a railway line and is close to the rails but a little to one side, experience shows that the discharge will be so badly biased by the close proximity of the rail that a measurement of current density in a vertical direction will not be representative of the actual flow from the pipe. The same statement applies to the case of a pipe paralleling another near-by pipe or cable system. In these cases the only accurate means of determining the current discharge around the pipe is to make an observation in six or eight different directions around the pipe. On the other hand, if the rails paralleling the pipe are at a distance of 10 or 12 feet or more, the discharge in a vertical direction is usually a fairly reliable criterion of the condition of the pipe except where lateral earth gradients are high.

3. MEASUREMENT OF LATERAL CURRENT DISCHARGE BETWEEN SUBSURFACE STRUCTURES

Where it is desired to measure the current flow in a lateral direction, as, for example, the current discharge from one pipe to another, this can be done by driving two holes in the region midway between the two pipes and to a depth about equal to the depth of the pipes. There is then put in each one of these holes a type C nonpolarizable

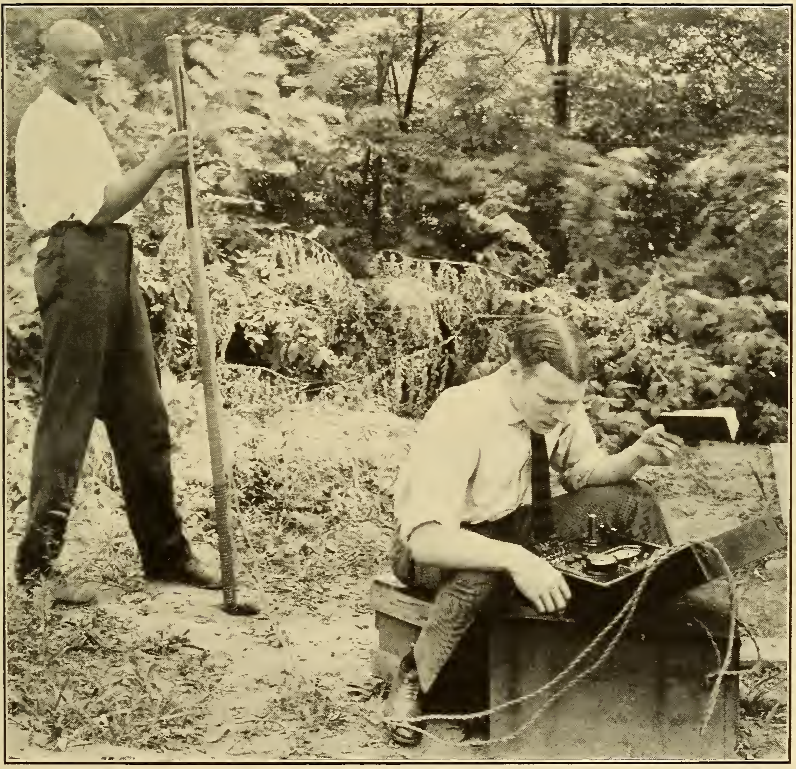


FIG. 13.—*Use of cantilever contactor*

electrode, as shown in Figure 14. The electrodes are placed in contact with the bottom of the holes and the leads from them are connected to the binding posts P_1 and P_2 (fig. 3). The reading of the voltmeter is then taken. The electrodes are then removed from the holes and the four-terminal cantilever contactor is placed in either hole and the two readings, corresponding to I_c and E_c in the procedure described above, are taken. The three values thus obtained are then substituted in equation (8), and the value of i in the earth between the electrodes is calculated. In this case a different constant Q' has to be used. Q' is equal to $\frac{Q}{S}$, where S is the ratio of the distance (in inches) between the two holes to the distance between P_1 and P_2 of the four-terminal contactor used. Of course, an excavation can be made if desired in lieu of the two holes and the leakage current can be measured in the ends of the excavation as previously described. This is particularly desirable in cases where the pipes are parallel to each other and rather close together. If they are too close to permit the insertion of a standard contactor between them, the proper procedure is to place the standard contactor against the wall of the trench at any suitable point for making the resistivity part of the measurement; that is, the crank measurement, and use two separate electrodes at whatever distance apart the conditions will permit for the potential measurement. When the trench contactor is used for the crank measurement, the constant in equation (8) becomes as above, $Q' = \frac{Q}{S}$, where S is the ratio of the distance between the two potential electrodes to the distance between P_1 and P_2 of the trench contactor.

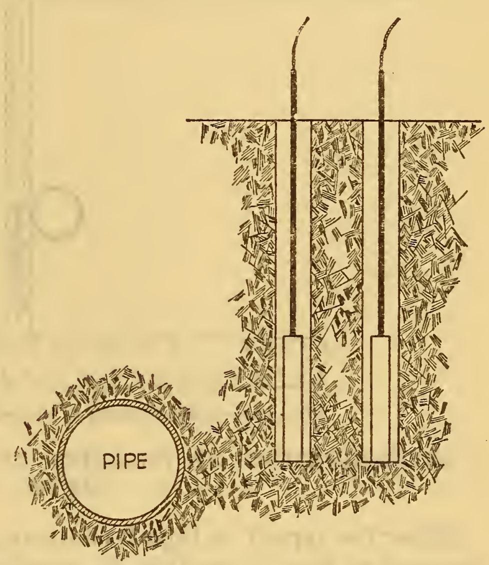


FIG. 14.—*Use of type "C" electrode*

4. MEASURING DISCHARGE BETWEEN TWO SUBSURFACE STRUCTURES AT CROSSINGS

Where two pipes or other subsurface structures cross at an angle, and it is desired to measure the current between them, the type B contactor may be put down in the manner shown in Figure 15. Here it will be seen that the hole is put down immediately beside the upper pipe, and should preferably be within a few inches of the side of the pipe and deep enough to permit placing the contactor approximately midway between the two pipes. The current density is then measured in exactly the same way as described above. Unless the position of the pipes is very accurately known, however, it is desirable, in making tests under these conditions, to make an excavation and use the type A or trench contactor, as in this way the contactor can be placed in its proper position with much greater certainty.

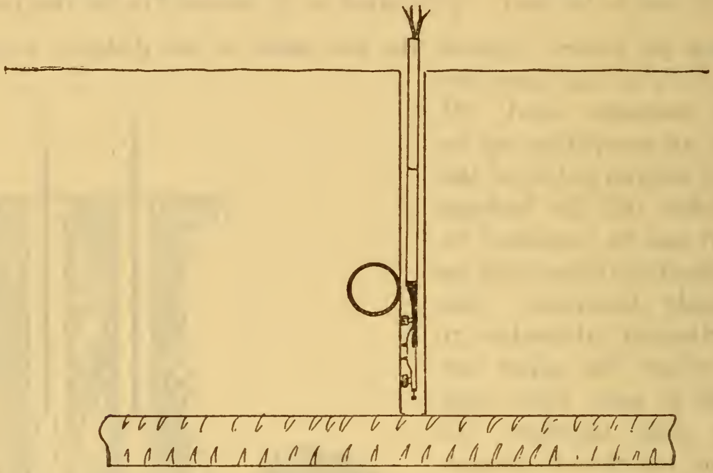


FIG. 15.—*Measurement of current at pipe crossings*

5. DETERMINATION OF POLARITY OF PIPE WITH RESPECT TO EARTH

Either the type A or type B contactor is used and the procedure is the same as that for reading E_e described under "1. Measurements of earth currents with trench contactor." If the voltmeter deflects to the right, the pipe is positive to earth; if to the left, negative.

6. MEASUREMENT OF RESISTIVITY OF THE EARTH

To measure the earth resistivity one has only to take the values of I_c and E_c obtained as in making the measurement of earth current. The resistivity r in ohm-centimeters is obtained from the formula (9)

$$r = A\frac{E_c}{I_c}$$

where E_c is in volts and I_c in milliamperes. The values of A are given on page 727.

In measuring earth resistivity there is a possibility of error due to the resistance immediately surrounding the potential terminals.

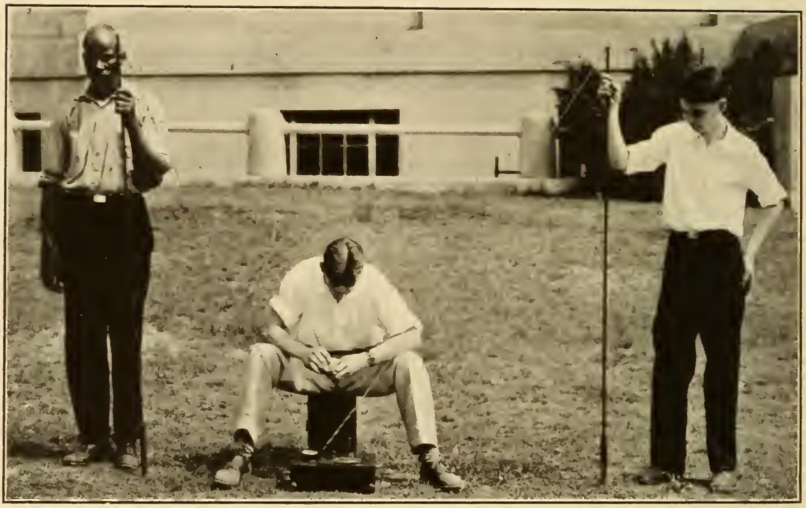


Fig. 16.—*Testing with type "C" electrode*

This is appreciable only when the earth resistivity is very high and the low range of the voltmeter is being used. If the earth resistivity is not over about 6,000 or 7,000 ohm-centimeters, any of the voltmeter ranges may be used, but if the resistivity is much in excess of this it is best to use the 1.0 volt or higher range. To be certain that the contact resistance is negligible, two voltmeter ranges may be used. If the contact resistance is small, the results of the two measurements should check.

It is important to bear in mind that earth resistivity varies greatly even within a small space on account of slight changes in porosity, the amount of stone or gravel present, temperature differences, and slight changes in moisture content. For these reasons a number of resistivity readings taken in different parts of the same hole will often vary as much as 50 per cent or more. The average of two or three readings should be used.

7. MEASUREMENT OF POTENTIAL DIFFERENCE WITH EXPLORING ELECTRODES (TYPE C)

At times it will be desirable to measure the potential difference between two points in the earth at various locations either on or below the surface. This is done by using a pair of exploring or type C electrodes, as shown in Figure 16. They are connected to the binding posts P_1 and P_2 (fig. 3) as described above, in measuring the lateral discharge. The switch, *9*, is set on the position marked "Potential" and the multiplier, *11*, is set to as high a resistance as practicable. The voltmeter then indicates the voltage between the two points at which the electrodes are in contact with the earth. The voltmeter deflects to the right when binding post P_1 is positive.

8. USE OF TEST-SET VOLTMETER AS A MILLIVOLTMETER

As ordinarily used, the voltmeter in the test set has a very high resistance in series with it, varying with the setting of the voltmeter multiplier. However, by pressing the key, *10* (fig. 3), this series resistance is short-circuited and the instrument can then be used directly as a millivoltmeter, having a full-scale deflection for 5 millivolts, correct at about 20° C., and having a temperature coefficient equal to that of copper. This scale can not be used with the nonpolarizable electrodes, but is sometimes useful for making very small voltage measurements. It is unsatisfactory for determining the voltage along a short continuous section of pipe or rail because of the very long period of the instrument under such conditions.

9. TESTING AND REPLACEMENT OF BATTERY

The battery used in this set may require replacement as often as once in six months. The battery is a standard 22.5-volt B battery, small size, and can be purchased from any electrical supply store. In order to determine whether the battery is in good condition, the switch, *14* (fig. 3), is set on the point marked "Battery test" and the binding posts C_1 and C_2 are short-circuited. The milliammeter should then read approximately 9 to 10 milliamperes. If the reading is much less than this, the battery should be replaced. To do this the door in the bottom of the test set should be opened. This exposes the battery, and the replacement is easily accomplished.

10. CARE OF TEST SET

Leakage within or over the surface of the earth-current meter may occur when it becomes dirty or has been exposed to moisture for considerable periods. For this reason it is advisable to keep the instrument free from dust and avoid testing on damp or rainy days. Leakage will be indicated by a deflection of the voltmeter when the current circuit is closed by a pressure on the commutator crank, with the commutator switch in the commutator position and the contactor leads disconnected. The leakage is usaully due to a dirty commutator, but may be due to moisture or other causes.

If there is any evidence of leakage within the test set, as indicated by deflection of the voltmeter when the set is not connected to external leads, the entire commutator, including the space between the two halves, should be thoroughly cleaned and the small diagonal grooves in the insulating segments of the commutator should be scraped out. As a matter of routine, the commutator should be cleaned periodically and a single drop of sewing-machine oil added to each of the bearings.

The voltmeter is of the semisuspended, single-pivot type. To give best results the suspension should be so adjusted as to remove practically all of the weight of the moving system from the pivot but still leave the pivot actually touching the jewel to give stability to the pointer. If the suspension is allowed to get too low, the jewel friction will be excessive, and if the suspension is drawn up too high, thus lifting the pivot out of jewel, the instrument will be unduly sensitive to vibration. The cap at the top of the suspension post is removable, permitting access to the adjusting nut; turning this to the left raises the suspension and turning it to the right lowers it. When the readings are being taken with the crank turning, there will be no hysteresis errors in the voltmeter due to pivot friction. If the reading E_e, however, is taken when the crank is not used, there may be slight jewel friction which can be entirely eliminated by gently tapping the instrument while the reading is being taken. The tapping should be extremely light, as too heavy tapping may cause the pointer to creep. Should this hysteresis error become too large, it indicates the need of slightly raising the suspension.

The push button at the right of the suspension post is provided for locking the moving system when the test set is being moved or transported. Provision is made so that when the cover is closed this button is automatically depressed, thus taking care of the locking of the moving system. If for any reason it is necessary to move the instrument with the cover open, care should be taken to depress this push button and turn it a fraction of a turn to the right, which locks it in position. The button at the left of the suspension post is a zero adjuster for the voltmeter. Figure 2, previously referred to, gives a complete wiring diagram of the test set.

Upon filling the potential electrodes with copper sulphate there is likely to be a small difference of potential (usually from 2 to 10 millivolts) between them, and this may persist for some minutes or even hours. It is important, therefore, before making observations to determine whether any natural difference of potential exists between the electrodes, and this is most easily accomplished by placing the contactor in a shovel full of fresh moist earth placed on a dry pavement or board or in any manner where it will not be traversed by stray currents. If under such conditions a potential difference between the electrodes is indicated by the voltmeter, a corresponding correction should be made in all subsequent measurements or the contactor should be allowed to remain in the earth with the electrode circuit closed through the voltmeter until the potential difference between the electrodes disappears. This will usually take from 30 minutes to an hour after the cups have been filled. This test for a natural or inherent potential between the electrodes should be made every time the cups are refilled and in fact at intervals throughout the day while routine testing is in progress.

11. CARE OF ELECTRODES

The terminal plugs should be kept in a bottle of copper sulphate when not in use, and the cups should be filled with copper sulphate each morning before starting measurements. It is well to remove the caps occasionally and refill the cups if they show a tendency to lose electrolyte. At the close of the day, remove the copper sulphate; otherwise it may crystallize in the threads of the caps and make it impossible to remove them. Do not screw a cap on tight with a dry plug. The plug will swell when it absorbs moisture and make it difficult to remove the cap. Keep the electrode leads dry. Moisture will cause leakage between current and potential leads and result in erroneous readings. Unless the contactor is waterproof keep it as clean and dry as possible to avoid leakage.

Occasionally a contactor develops a weak spot in the insulation of one of the leads, or moisture enters the contactor itself. This causes galvanic potentials large enough to affect seriously the computation of leakage current. It is advisable, therefore, to test the contactor occasionally either by placing it in an insulating vessel filled with water or by placing it on clean earth, preferably free from stray currents. If a vessel of water is used, the vessel must be nonmetallic and contain no metal. If the contactor is tested by placing it on earth, the electrode should be reversed after the θ_e observation is made, the terminals being placed in the depressions made when the contactor was in the first position. Since the test is of the potential terminals, it is better to disconnect the current terminals from the meter during the test.

Assuming that the stray current is negligible, or constant, one-half the algebraic sum of the two θ_e deflections is the deflection due to galvanic action in the electrode. If an appreciable deflection is obtained, the electrode cups should be cleaned and refilled, since unequally oxidized cups, empty cups, or dirty copper sulphate may be the source of the potential.

Moisture or wear may also cause a leakage between the current and potential circuits of the contactor. In all cases these leakage effects are much greater when the instrument is on open circuit than when the contactor is placed in contact with the earth, because in this latter position the earth, in effect, short-circuits the leakage path.

To test for such leakage interconnect the instrument terminals C_1 and P_2; connect contactor terminals P_1 and C_1 to instrument terminal P_1 and contactor terminals P_2 and C_2 to instrument terminal C_2. Place the voltmeter switch, *11*, on the 10-volt range, and the commutator switch, *9*, on commutator. Press the crank lever, *12*, sufficiently to close the battery circuit, but do not rotate the commutator. A deflection of the voltmeter indicates a leak between the potential and current circuits. If there is no deflection, lower voltmeter scales should be tried. Any movement of the commutator, however, may produce a deflection of the voltmeter due to induction.

Some of the contactors on which all four leads are inclosed in a rubber case show an inductive effect when the electrode terminals are connected to the instrument in the usual way if the commutator is turned while the contactor is on open circuit. This effect disappears when the contactor is in the earth, as may be seen by short-circuiting the current terminals of the contactor.

If it is found necessary to replace the electrode leads, care should be taken to have the current leads twisted together. If a potential and a current lead lie side by side throughout their lengths, a very considerable inductive effect is obtained when the θ_c reading is taken. The magnitude of this effect depends on the length of the leads, the commutation frequency, and the current used. It may, under some conditions, cause a serious error which is avoided in the original construction of the contactors.

III. SIGNIFICANCE OF READINGS OBTAINED WITH THE EARTH-CURRENT METER

1. ACCURACY OF INSTRUMENTS AND OBSERVATIONS

The correct manipulation of the earth-current meter and the contactor is, after the operator has obtained a little experience, a simple matter. It should be understood that the earth-current meter indicates not merely stray currents originating in the circuits of street railway lines, but the resultant of all direct currents flowing between the potential electrodes. This may include, and in some cases consists entirely of, current due to galvanic action originating either in soil conditions or the presence of two electrically different metals. Occasionally these galvanic currents are sufficient to cause such a deflection of the earth-current meter as to indicate a serious rate of corrosion. For example, under favorable circumstances it is possible to pick up with a 4½-inch contactor evidences of current flowing between a corroded and an uncorroded point on a section of a pipe providing the path of this current is long enough to include both the potential terminals of the electrode. However, the contactor picks up but a component of this current and it is not possible to compute the true galvanic current from the reading obtained. If the galvanic circuit is very short, as is often the case, the earth-current meter will be only slightly affected, if at all.

In case the deflection of the instrument varies irregularly following more or less closely the cycle shown by a potential difference measurement between the structure under observation and an adjacent structure, or the earth, the presence of street-railway current may usually be assumed. If the deflection is such as to indicate a serious leakage current, it may be assumed that the galvanic potentials involved are unimportant. In certain cases, however, especially when the deflections are small, it may be necessary to determine the galvanic current by repeating the test at night or at some other time when the street-railway current is cut off.

It may also be necessary to test and correct for the small galvanic potentials which frequently originate in the contactor itself as explained in the discussion of the care of electrodes. Such tests should be made frequently if the deflections are less than five scale divisions and the 0.1-volt scale is used.

The determination of whether a set of data is free from errors, whether it has been obtained at a significant location, and its significance with reference to specific or general electrolysis conditions calls for the exercise of considerable judgment.

Perhaps the first question to be considered is the accuracy of the instrument. The equation for leakage current, $i=Q\frac{E_eI_c}{E_c}$, involves a contactor constant, an ammeter, and two voltmeter readings.

The determination of the contactor constant has already been discussed. The accuracy of the meter indications depends not only on the construction of the instrument but on the conditions under which it is used.

The voltmeter when new is guaranteed by the manufacturer to be accurate to 2 per cent of the full-scale reading. The original instrument error is due to three causes: Instability of the final position of the pointer, inaccuracy in scale adjustment, and errors in the adjustment of the instrument resistances. After the instrument has been used for some time the error, due to the instability of the position of rest of the pointer both when in the zero position and when deflected, increases. This is due to the low torque of the suspension necessary for so sensitive an instrument and to the development of slight pivot friction. When the instrument is properly leveled and adjusted the uncertainty of the position of rest should not be more than one scale division or 2 per cent of full-scale deflection.

The error in the case of the θ_c reading is less on account of the slight vibration of the instrument when the crank is turned, and the errors in the θ_e readings will nearly cancel out, since about as many readings will be approached from higher as from lower values. It is safe to assume, therefore, that while the instrument remains in good condition the voltmeter errors will not greatly exceed 2 per cent of full-scale value and that since one occurs in the numerator and the other in the denominator of the equation for leakage current, the net error will be small when θ_e and θ_c are of about the same magnitude. The magnitude of θ_c can be largely controlled by varying I_c. The ammeter is accurate within 1 per cent, but because of vibration and commutation the observation of the I_c value may involve an additional error in reading of half a scale division or about 1 per cent of full-scale deflection. The vibration due to commutation is a minimum when the commutator is clean and the brushes in good condition. It will be found that the ammeter reading when the crank is held in one position is about 10 per cent greater than when the commutator is turned, because of the insulation of the commutator. This, of course, does not involve any error since the voltmeter reading θ_c shows the same percentage difference under the two conditions.

Whether the result of an individual test is dependable may often be determined by its relation to other tests in the same locality. Apparently contradictory results may often be explained. Equations have been developed and methods described above for determining the leakage current in the earth when the lines of current flow are parallel and when they diverge radially from a pipe. Occasionally a pipe is found across which current flows and which really has little effect on the earth currents. In such cases the current on opposite sides of the pipe will be equal in magnitude but opposite in direction with respect to the pipe, while the currents at right angles to these two will be very small. To determine whether the pipe should be considered the source of current and the constant R used, repeat the measurements with the electrode farther from the pipe. If the E_e readings are not reduced the lines of current flow do not originate in the pipe.

It has been pointed out in the discussion of earth resistivity measurements that the resistivity of the soil varies greatly from place to place and changes with its moisture and temperature. This, of course, affects the distribution and amount of current collected or discharged by a pipe. Surface conditions of the pipe also affect the distribution of the leakage current. While it has been shown that a pipe must be within a few inches of the electrode to affect the resistivity measurement, the effect of a metallic structure on the leakage current may extend over a large area if it has a potential considerably different from that of the pipe under investigation.

2. EXAMPLES OF EARTH-CURRENT METER DATA

The complex conditions which result from variations in soil resistivity and the presence of a number of metallic structures in a street are well illustrated by data secured by A. J. Fecht in the course of an investigation conducted jointly by the research subcommittee of the American Committee on Electrolysis and the Bureau of Standards. Figures 17, 18, 19, and 20 are taken from Mr. Fecht's report and show how many data are necessary in order to obtain a true picture of electrolysis conditions at a given location, and how inadequate is the information obtainable without the use of the earth-current meter.

Figure 17 shows the relative positions of the structures in the street. It will be noted that there are present only those found in any well-developed neighborhood. In many localities there will be in addition a duct line for power cables, and additional water or gas mains are not uncommon. An oil line or steam-heating line is also found occasionally.

Figure 18 illustrates electrolysis conditions around the telephone-duct line and the water main. The leakage current is plotted by means of polar coordinates; the dash circle being the circle of reference. Values within the circle are negative; that is, the current flows toward the structure while the values outside the circle are positive, indicating that the current flows away from the structure. It is not possible to reduce earth-current measurements to rates of discharge from a conductor within a duct line because of the effect of the duct,

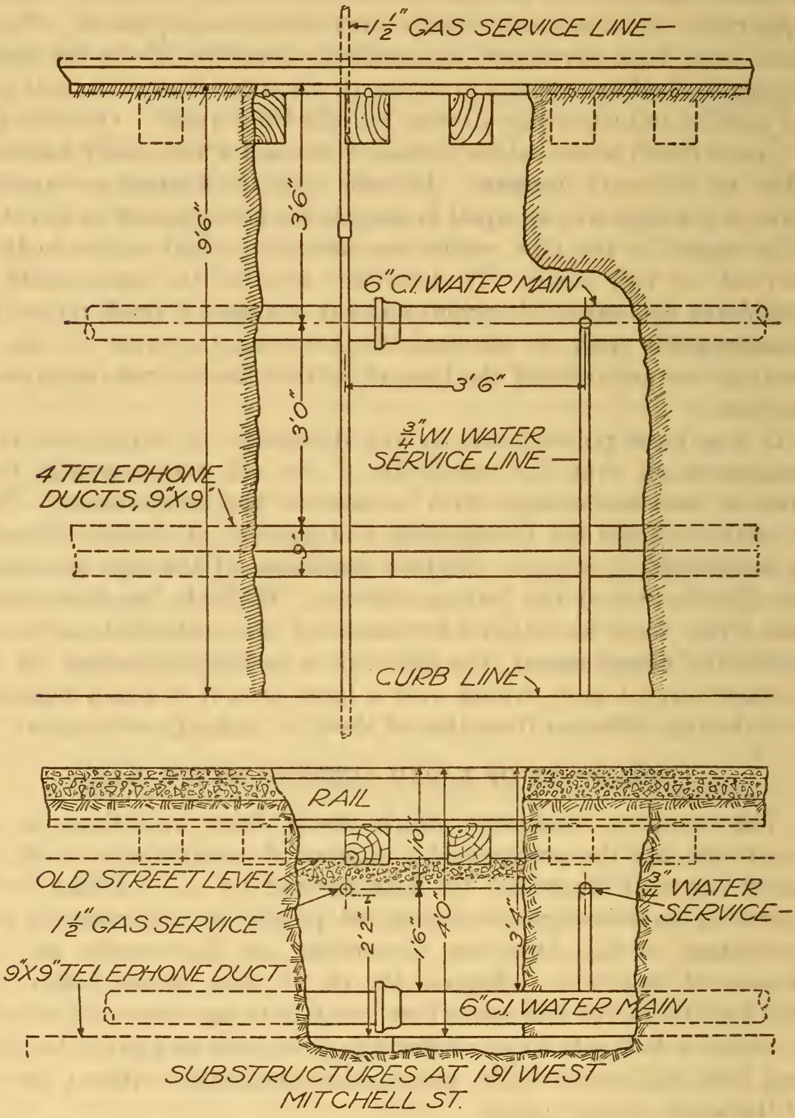


FIG. 17.—*Relative position of structures at test locations*

and it is necessary to express the leakage current in the neighborhood of a duct line simply as the current density in the earth at the point of test, usually in milliamperes per square foot of earth normal to the electrode. When the lines of current flow diverge from the duct line, the magnitude of the leakage current values will decrease as the distance from the cable in the duct increases, and the significance of the figures is not so definite as in the case of those taken with respect to a conductor in direct contact with the earth. In the latter case the leakage currents are expressed in milliamperes per square foot of conductor surface. Figure 18 shows that the current flows toward the water pipe on the side remote from the duct line and away from the pipe on the side near the duct. There is no discharge in the direction of the street-car track. The potential-difference measurements indicate that all the underground structures are negative with respect to the rail and on this basis would be regarded as in a safe condition. Records show that both gas and water services have failed in this neighborhood where they cross the duct line. Incidentally it might be mentioned that a drainage system was in operation on both the telephone and the water lines as a means of electrolysis mitigation.

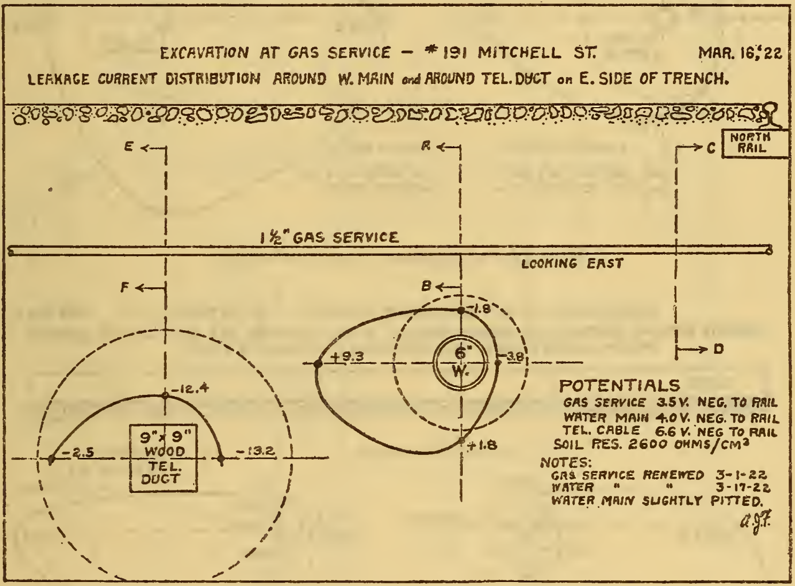

EXCAVATION AT GAS SERVICE – #191 MITCHELL ST.
MAR. 16,'22
LEAKAGE CURRENT DISTRIBUTION AROUND W. MAIN and AROUND TEL. DUCT on E. SIDE OF TRENCH.
E
A
C
NORTH RAIL
1½" GAS SERVICE
LOOKING EAST
F
B
D
-12.4
-2.5
-13.2
9"×9" WOOD TEL. DUCT
-1.8
+9.3
6" W.
-3.8
+1.8
POTENTIALS
GAS SERVICE 3.5 V. NEG. TO RAIL
WATER MAIN 4.0 V. NEG. TO RAIL
TEL. CABLE 6.6 V. NEG TO RAIL
SOIL RES. 2600 OHMS/CM³
NOTES:
GAS SERVICE RENEWED 3-1-22
WATER " " 3-17-22
WATER MAIN SLIGHTLY PITTED.
A.J.F.

FIG. 18.—*Condition around telephone duct line and water main*

Figure 19 shows the conditions at two points on the gas service pipe, the figure on the left showing conditions where the service crosses over the water main and the one on the right showing conditions near the street-car rail. The first of these shows some discharge of current downward toward the water main and a much greater discharge toward the duct line. Figure 18 also shows a flow of current toward the water main at this point. The other part of Figure 19 shows that the service is discharging current on all sides except that nearest the rail, the maximum discharge being in the direction of the duct line. In Figure 20, in addition to the leakage currents from the gas and water services where they cross the telephone duct, the corresponding soil resistivities are shown in broken curves.

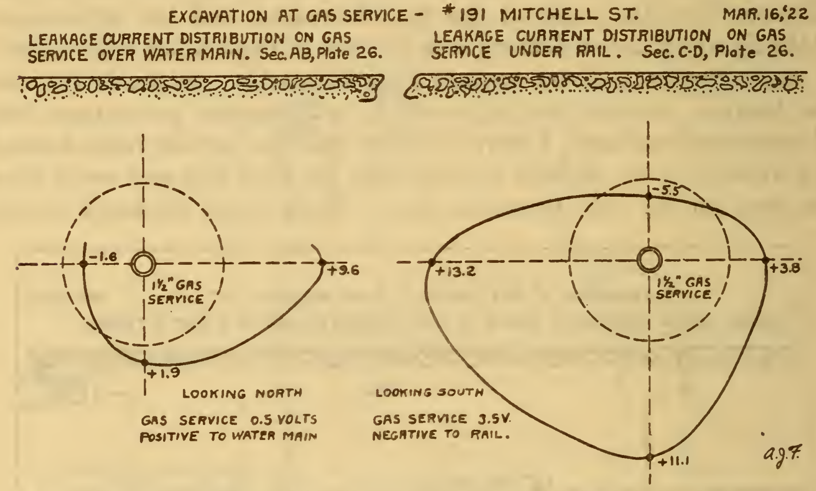

EXCAVATION AT GAS SERVICE - #191 MITCHELL ST. MAR. 16,'22
LEAKAGE CURRENT DISTRIBUTION ON GAS SERVICE OVER WATER MAIN. Sec. AB, Plate 26.
LEAKAGE CURRENT DISTRIBUTION ON GAS SERVICE UNDER RAIL. Sec. C-D, Plate 26.
-1.6
1½" GAS SERVICE
+9.6
+1.9
LOOKING NORTH
GAS SERVICE 0.5 VOLTS POSITIVE TO WATER MAIN
-5.5
+13.2
1½" GAS SERVICE
+3.8
LOOKING SOUTH
GAS SERVICE 3.5V. NEGATIVE TO RAIL.
+11.1
a.g.F.

Fig. 19.—*Condition along gas service*

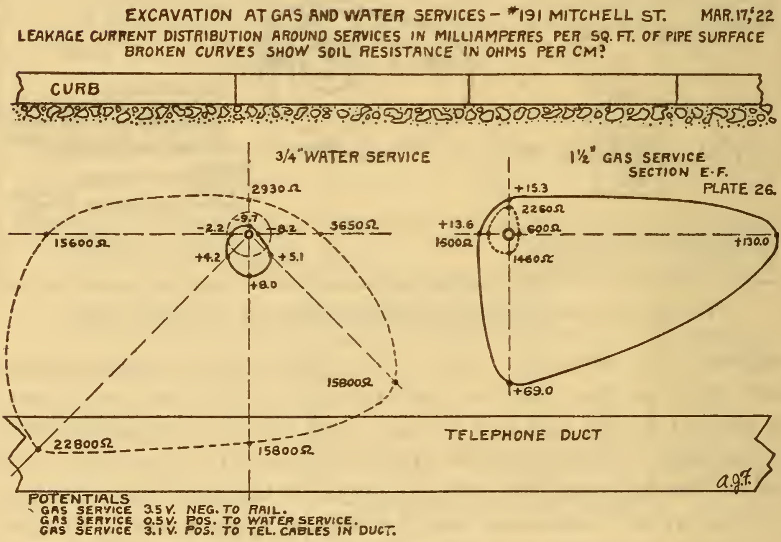

EXCAVATION AT GAS AND WATER SERVICES - #191 MITCHELL ST. MAR. 17,'22
LEAKAGE CURRENT DISTRIBUTION AROUND SERVICES IN MILLIAMPERES PER SQ. FT. OF PIPE SURFACE
BROKEN CURVES SHOW SOIL RESISTANCE IN OHMS PER CM³
CURB
3/4" WATER SERVICE
2930 Ω
-9.7
-2.2
-8.2
3650 Ω
15600 Ω
+4.2
+5.1
+8.0
15800 Ω
22800 Ω
15800 Ω
1½" GAS SERVICE
SECTION E-F.
PLATE 26.
+15.3
2260 Ω
+13.6
600 Ω
1600 Ω
1460 Ω
+130.0
+69.0
TELEPHONE DUCT
a.g.F.
POTENTIALS
GAS SERVICE 3.5 V. NEG. TO RAIL.
GAS SERVICE 0.5 V. POS. TO WATER SERVICE.
GAS SERVICE 3.1 V. POS. TO TEL. CABLES IN DUCT.

Fig. 20.—*Relation of gas and water services to duct line*

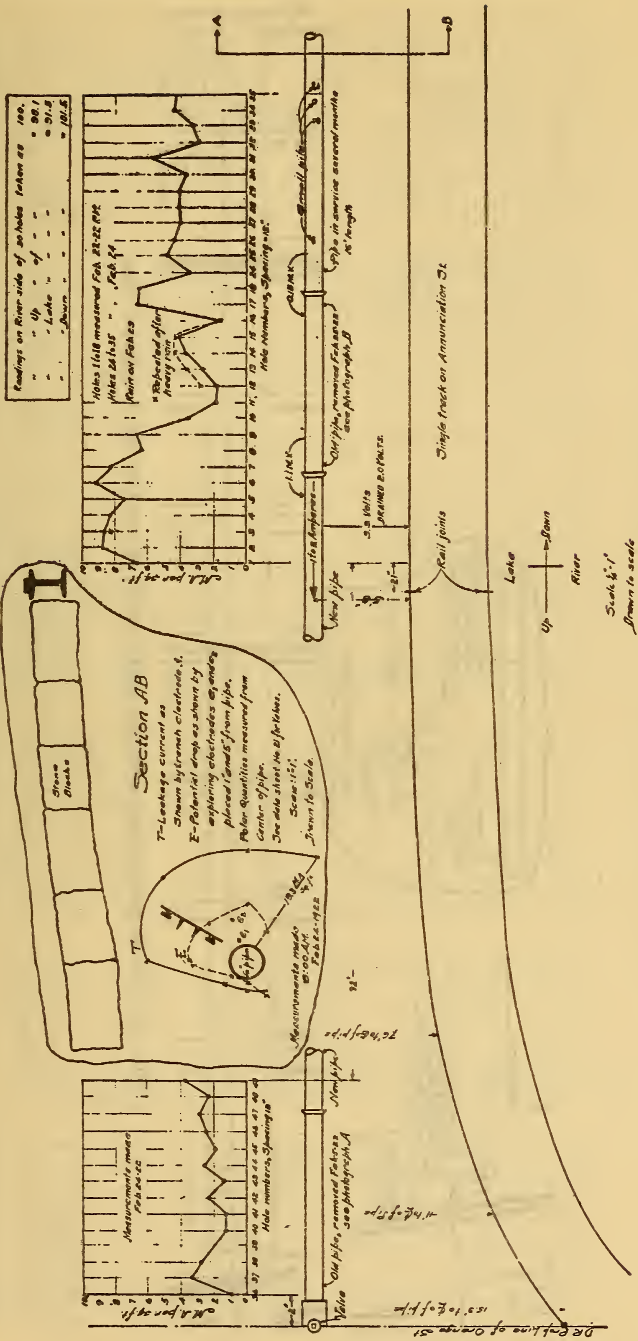

A
B
Readings on River side of 20 holes taken as 100.
" " Up " " " 90.1
" " Lake " " " 91.8
" " Down " " " 101.8
Holes 11 & 18 measured Feb. 22-22 P.M.
Holes 28 to 35 " Feb. 24
Rain on Feb. 23
Repeated after heavy rain
Hole Numbers, Spacing 18"
M.A. per sq. ft.
Small pipe
Pipe in service several months 16' length
Old pipe, removed Feb. 22 see photograph B
New pipe
1.1 M.V.
0.8 M.V.
1.10 Amperes
3.9 Volts
DRAINED 2.0 VOLTS
Single track on Annunciation St.
Rail joints
Lake
Up
Down
River
Scale 1/8"=1'
Drawn to scale except pipe diameter
Section AB
T-Leakage current as shown by trench electrode S.
E-Potential drop as shown by exploring electrodes E1 and E2 placed 1' and 5' from pipe.
Polar Quantities measured from Center of pipe.
See data sheet No. 2 for values.
Scale 1:4
Drawn to Scale.
Stone Blocks
T
E
pipe
Measurements made 8:00 A.M. Feb 22-1922
Measurements made Feb 22-22
Old pipe, removed Feb. 22 see photograph A
Hole numbers, Spacing 18"
Valve
26.6 of pipe
11.8 of pipe
153.1 of pipe
DR End line of Orange St.

FIG. 21.—*Variation in leakage current along a pipe line paralleling street car tracks*

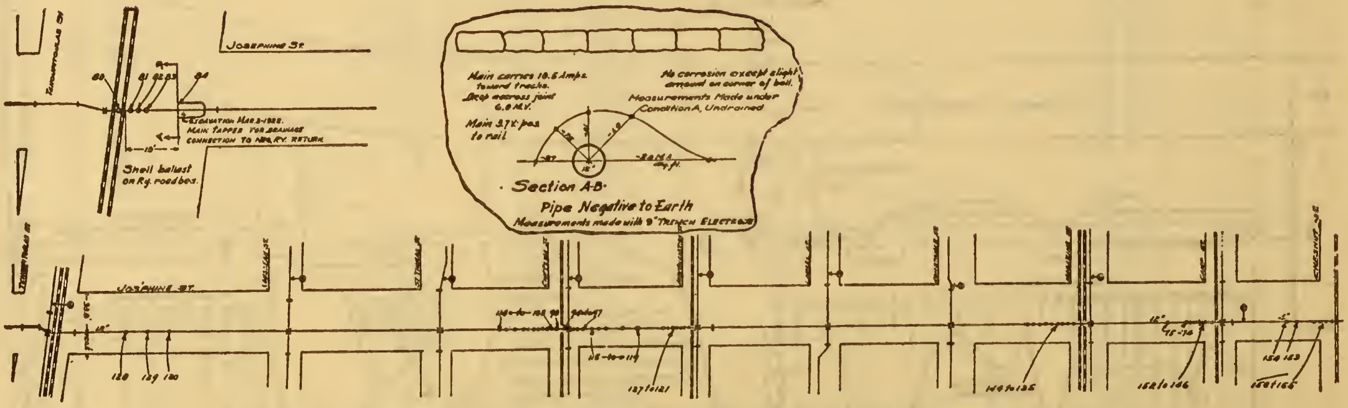


Fig. 22.—*Earth-current measurements and location of test holes on Josephine Street*

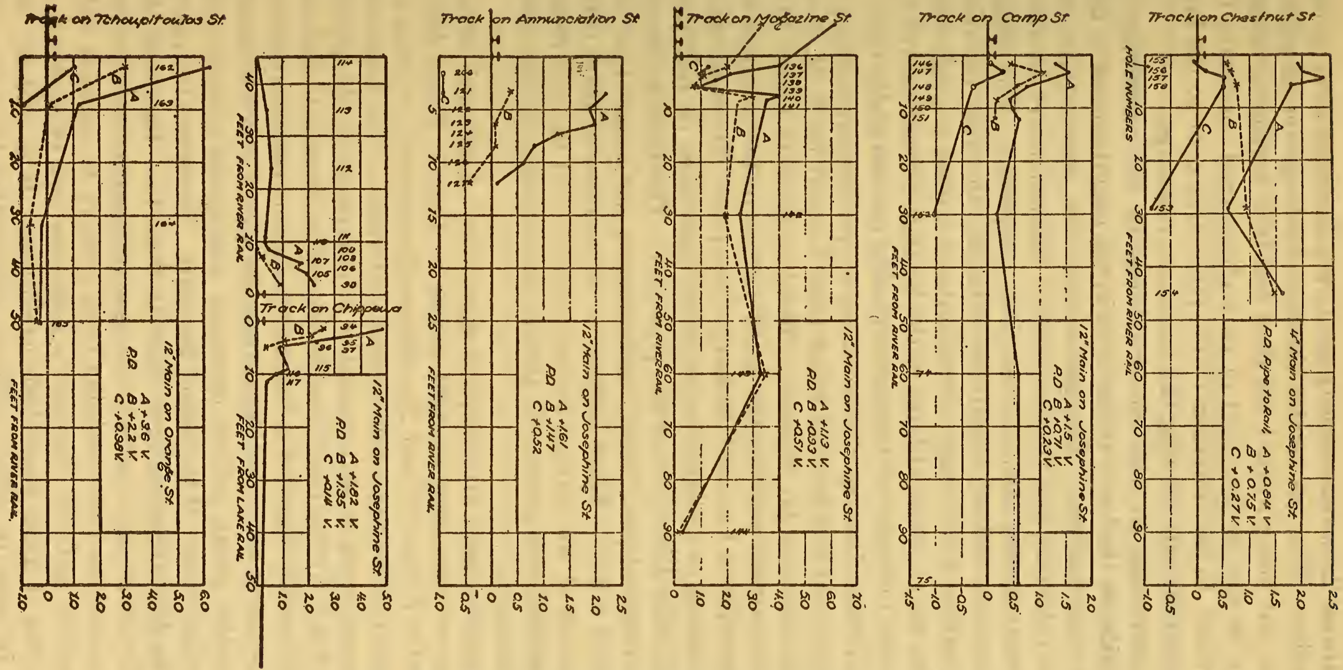


FIG. 23.—*Earth-current measurements with and without drainage*

(All pipes run at right angles to car tracks.) Measurements made by means of a 4-terminal contactor 2½-inch holes drilled vertically over water mains. A, water mains not drained; B, water mains drained at drainage points 7, 8, and 15 only; C, water mains drained at 16 points. Positive leakage indicates that pipes are discharging current; negative leakage indicates that pipes are collecting current

The data on the water-service pipe show a discharge directly toward the duct line. The gas service shows a discharge on all sides, the maximum not being toward the duct but in a horizontal direction. This may be due to the effect of an undiscovered conductor in the neighborhood, to the condition of the pipe surface, or to the low soil resistance on the side showing the maximum discharge.

It is interesting to note the variations in soil resistivity. Mr. Fecht attributes the lower resistivities in the neighborhood of the gas service to gas leakage. The gas service was renewed two weeks previous to the test, and the condition of the water service was such that it was renewed after the test was completed. The ranges of leakage currents and soil resistivities illustrate the wide variations in these quantities which may be encountered within a single excavation. The unsymmetrical form of the leakage-current curves is due largely to the influence of structures crossing the one under test.

The variation of leakage current along a pipe line paralleling a track is well illustrated in Figure 21 taken from a report by E. R. Shepard on a study similar to Mr. Fecht's. The data given in Figure 21 were taken to determine whether the earth-current meter readings would show effects due to localized discharge from pits. The readings were made by means of a cantilever contactor and taken on four sides of a 2½-inch hole directly over the pipe line. The leakage current is shown to vary between 2 and 9 milliamperes per square foot within a distance of 6 feet. There appears to be no close relation between the magnitude of the leakage current readings and the pits found on the pipe when it was uncovered; that is, the readings indicate average current discharge.

In the same report Mr. Shepard shows very clearly the effects of car tracks on pipe lines at right angles to them. These data are reproduced in Figures 22 and 23. Figure 22 shows the location of the test holes and of the pipes with respect to the rails. The insert shows conditions as found in an excavation at one point on the pipe line. The pipe was 3.7 volts positive with respect to the rail 10 feet away, a condition usually regarded as indicating a serious electrolysis hazard. The earth-current meter indicated that the pipe was not discharging current at this point and no corrosion was found except a slight amount on the corner of the bell of the joint. However, the pipe was found to be discharging current closer to the rails. Figure 23 shows how rapidly the leakage currents decrease as distances from the tracks increase, sometimes even changing from positive to negative values.

Mr. Fecht's and Mr. Shepard's data are not exceptional, but representative of usual electrolysis conditions. It is evident, therefore, that in order to collect sufficient information for a true representation of any electrolysis hazard a large number of observations must be made, and that the selection of the test points largely determines the character of the results obtained.

It is for this reason among others that it is advised that the determination of electrolysis conditions be assigned to some one who is thoroughly familiar with such work.

3. PERMISSIBLE LEAKAGE CURRENTS

The determination of what constitutes a dangerous amount of current flowing from a pipe may be reached through computations or field experience and depends somewhat on the thickness of the pipe and upon local conditions affecting the distribution of the leakage current over the pipe surface. The earth-current meter indicates the average current density over a considerable area of pipe surface. The rate of removal of metal from an iron anode is approximately 1 gm. per ampere hour or 20 pounds per ampere year. When the leakage current density and the specific gravity of the metal are known it is therefore possible to compute the volume of iron removed per unit of pipe surface, and hence the time required for all the metal to be removed. However, since the intensity of current discharge is not uniform, an assumption must be made of the relation between the maximum and the average rate of penetration. This depends upon circumstances. Factors of from 5 to 20 or more have been assumed. Having chosen what appears to be a reasonable factor it is possible to estimate the time required for the pipe to be penetrated, and thus to determine whether the observed leakage current density is sufficient to shorten materially the useful life of the pipe.

The other method of determining the permissible leakage current is by comparing the earth currents found in various places with the observed condition of the pipe under test. From this comparison and the age of the pipe its rate of deterioration can be estimated if electrical conditions have not changed.

In the work done thus far with the earth-current meter it has been found that in places where no serious trouble is in progress the leakage currents have usually not exceeded 1.0 milliampere per square foot of pipe surface. Higher values have usually been found where material electrolytic corrosion is in progress, and in very bad areas values of 10 milliamperes per square foot, and sometimes much higher, are found. All of these figures should be regarded as somewhat tentative, and the question of permissible leakage currents should be further investigated.

IV. SIGNIFICANCE OF LETTERS USED IN EQUATIONS

The units in parentheses are those used in computing the numerical values given in the text.

a = distance from P_1 to surface of pipe (inches),
A = constant for finding earth resistivity,
C_1 = current electrode nearest spacer end of contactor,
C_2 = current electrode nearest lead end of contactor,
D = diameter of pipe (inches),
E_e = voltage drop between P_1 and P_2 due to earth current (volts),
E'_e = voltage drop between P_1 and P_2 due to radial current (volts),
E_c = voltage drop between P_1 and P_2 due to battery current (volts),
i = leakage current (milliamperes per square foot),
I_c = current due to battery (milliamperes),
K = constant of voltage indicator,
L = distance between potential terminals (inches),
P_1 = potential terminal nearer spacer,
P_2 = potential terminal nearer lead,
Q = constant for finding leakage current in earth,
Q' = constant for finding leakage current in earth, with single electrodes,
r = resistivity of earth (ohm-centimeters),
R = constant for leakage current at surface of pipe,
$\theta_e = K E_e$ = deflection of galvanometer due to earth current,
$\theta_c = K E_c$ = deflection of galvanometer due to battery current,
S = ratio of distance between single terminal electrodes to distance between P_1 and P_2.

V. EQUATIONS

$$i=\frac{Q\theta_e I_c}{\theta_c}=\frac{QE_e I_c}{E_c} \tag{8}$$ (p. 687)

This equation is used for calculation of current density in the earth where lines of flow are parallel.

$$i=\frac{RE'_e I_c}{E_c} \tag{10}$$ (p. 699)

This equation is used for calculation of current density at the pipe surface.

$$R=\frac{2QL}{2.303\ D\log_{10}\left(1+\frac{2L}{D+2a}\right)} \tag{16}$$ (p. 701)

$$r=A\frac{E_c}{I_c} \tag{9}$$ (p. 710)

Constants

Contactors	In dry trench		In dry 2½-inch holes		Immersed	
	Q	A	Q	A	Q	A
4½-inch	6.8	12,000	6.15	13,200	4.5	18,000
9-inch	.87	47,000	.61	67,000	.54	75,000

These constants are calculated in different systems of units in order to conform to the practice commonly followed. The values of Q are such as to give i (equation (8)) in milliamperes per square foot when the current I_c is expressed in milliamperes. The values of A are related to the metric system so as to give r (equation (9)) in ohm-centimeters, when E_c is measured in volts. For values of R (equation (10)) for different sizes of pipe, see Tables 7 and 8, pages 701 and 702.

WASHINGTON, May 10, 1927.